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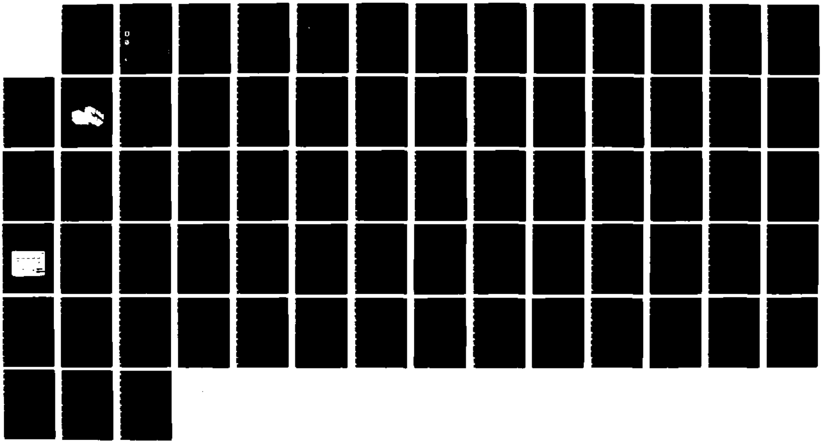

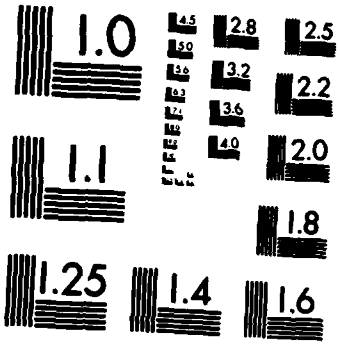

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Quadrupole Ion/Neutral Mass Spectrometer for Space Shuttle Applications

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7 April 1986

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IONOSPHERIC PHYSICS DIVISION PROJECT 4643
AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MA 01731

"This technical report has been reviewed and is approved for publication."

FOR THE COMMANDER

JOHN E. RASMUSSEN, Chief
Ionospheric Interactions Branch
Ionospheric Physics Division

ROBERT A. SKRIVANEK, Director
Ionospheric Physics Division

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A Quadrupole Ion/Neutral Mass Spectrometer (QINMS) was developed for the fourth flight of the Space Shuttle in June and July of 1982. Several additional instruments have been built for other programs using the same design. The instruments are designed to measure the neutral and positive ion composition in the vicinity of the Space Shuttle or similar satellites. Other experimental capabilities include the measurements of total neutral pressure, total ion density, and species kinetic energy distributions. This report describes in detail the design and construction of the QINMS instruments, the integration requirements, ground testing and calibration procedures, typical flight operations, and finally, data requirements.

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Quadrupole Ion/Neutral Mass Spectrometer for Space Shuttle Applications

1. INTRODUCTION

In June and July of 1982, the Ionospheric Interactions Branch (then the Composition Branch of the Aeronomy Division) flew a quadrupole mass spectrometer on the Space Shuttle Columbia. The instrument successfully measured the ambient ionosphere and thermosphere and also observed the effect of the Shuttle on the environment. Several reports and papers concerning these experiments have appeared in the literature.[1-4] To describe its capabilities, this instrument has been given the name Quadrupole Ion/Neutral Mass Spectrometer, or QINMS.

(Received for publication 3 April 1986)

1. Narcisi, R., Trzcinski, E., Federico, G., Wlodyka, L., and Delorey, D. (1983) The gaseous and plasma environment around space shuttle, AIAA-83-2659, AIAA Shuttle Environment and Operations Meeting, Washington, D. C.

2. Hunton, D.E., and Calo, J.M. (1985) Low energy ions in the shuttle environment: evidence for strong ambient-contaminant interactions, Planet. Space Sci. 33:945.

3. Hunton, D.E., and Calo, J.M. (1985) Gas phase interactions in the shuttle environment, AIAA-85-6055-CP, AIAA Shuttle Environment and Operations Meeting II, Houston, Tex.

4. Hunton, D.E., and Swider, W. (1986) Variations of water vapor concentration in the shuttle environment, J. Spacecraft and Rockets (submitted).

At present, the Branch is building a number of similar instruments to be flown on a variety of other Air Force Shuttle and satellite programs. These programs include the AFP-675 mission, the Combined Release and Radiation Effects Satellite (CRRES), the Interactions Measurement Payload for Shuttle (IMPS), and a surface interactions experiment to be conducted with NASA.

The purpose of this report is to bring together, in one place, a complete description of the mass spectrometer. Chapter 2 concentrates on the instrument itself, and includes discussions of the scientific capabilities and specifications as well as the mechanical and electronic design. The mass spectrometer is self-contained in that it does not depend on other instruments to make its measurements. Nevertheless, it must receive power and commands from and return the data to a larger spacecraft or payload. Chapter 3 is concerned with the integration of the instrument into such a larger spacecraft. Chapter 4 discusses the ground operations that must take place before a flight. It is divided into sections on in-house testing and calibration and on procedures that occur during integration. Chapter 5 presents a general discussion of in-flight procedures, and Chapter 6 is a discussion of data requirements.

2. INSTRUMENT DESCRIPTION

2.1 Scientific Objectives and Capabilities

The space surrounding the Space Shuttle while it is in orbit has been shown to be perturbed significantly by the degassing of Shuttle surfaces and by Shuttle operations such as thruster firings, water dumps, and flash evaporator operations.[1-13] The Quadrupole Ion/Neutral Mass Spectrometer (QINMS) instruments are designed to measure the composition and characteristics of this induced environment surrounding the Shuttle. In addition, the concentrations of ambient ionic and neutral species at the altitude of the Shuttle orbits are considerable.[14] The instruments are capable of observing these natural atmospheric constituents as well.

QINMS is a compact, fast sampling quadrupole mass spectrometer system with a variety of experimental capabilities. The primary purpose of the instrument is to measure the concentration and the identity of each constituent of the gas entering the sampling orifice. It is sensitive to neutral and ionic species, though not to both simultaneously. The two ways of operating the mass spectrometer are called ion mode and neutral mode. In practice, the concentration of

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References 5 through 14 will not be listed here. See References, page 63.

negative ions at Shuttle altitudes is small, and only positive ions and neutrals are sampled.

In addition to this composition information, the instrument measures the total pressure of the neutral gas in the neutral mode and the total density of the ion species in the ion mode. This information is provided by a grid, located between the ion source and the quadrupole rods, that collects a fraction of the total ion current leaving the ion source.

The sampling rates of the composition data and the pressure/density data are both fast enough to resolve transient effects in the environment such as ionospheric irregularities and Shuttle maneuvering thruster engine firings.[1] The calibration of both types of scientific data outputs will be discussed in the section on testing and calibration.

The final experimental capabilities come from an additional grid in the ion source that functions as a retarding potential analyzer (RPA). On the STS-4 flight, this grid was limited to a voltage range of -12 to +12 V. On other instruments, this range has been extended to -55 to +55 V. The RPA is used to obtain the kinetic energy distributions of the neutral and ionic species entering the mass spectrometer. From these distributions, the source of the species, either the contaminant cloud or the ambient ionosphere, can be surmised in some cases. Considerable information on the interactions that occur in the Shuttle environment between the ambient and contaminant species can also be obtained. Finally, if the RPA analysis shows a clear peak from one of the prominent ambient ions, such as O^+, the vehicle potential[15] can be derived. The use of this retarding potential analyzer and the results of the experiments on STS-4 have been discussed in detail by Narcisi et al[1] and by Hunton and Calo.[2,3]

The combination of capabilities designed into the QINMS instruments gives a uniquely powerful and versatile experimental tool. Nevertheless, the instruments use well established, standard methods. The fundamentals and theories of these methods are described in detail in the literature.[16-19]

2.2 Specifications

This section discusses the performance specifications for the two types of scientific data from the QINMS instrument, the pressure/density grid current and the electron multiplier current. A summary of the specifications is given in Table 1.

References 15 through 19 will not be listed here. See References, page 63.

Table 1. QINMS Specifications

Parameter	Value
Mass Spectrometer Characteristics:	
Mass Range	0-150 amu
Mass Resolution	$M/\Delta M$ = 30-50
Signal Dynamic Range	10^5
Sensitivity (Ion Mode)	5×10^{-11} amp = 10 ions/cm^3 5×10^{-6} amp = 10^6 ions/cm^3
Sensitivity (Neutral Mode)	5×10^{-11} amp = 10^{-9} Torr 5×10^{-6} amp = 10^{-4} Torr
Sampling Rate	100 Hz (max)
Spatial Resolution of Data Points	80 m
Ion/Neutral Mode Switching Rate	1/min (max)
Pressure/Density Grid Specifications:	
Signal Dynamic Range	10^5
Sensitivity (Ion Mode)	5×10^{-11} amp = 10^3 ions/cm^3 5×10^{-6} amp = 10^8 ions/cm^3
Sensitivity (Neutral Mode)	5×10^{-11} amp = 10^{-8} Torr 5×10^{-7} amp = 10^{-4} Torr
Sampling Rate	1000 Hz (optimum)
Spatial Resolution of Data Points	8 m

The mass range of the mass spectrometer is not an easily adjusted parameter, but it can be changed during construction of the instrument through a suitable choice of the rf frequency. The mass range cannot be changed during a flight. The range always starts at $m/e = 0$ and may extend as high as 150. For any particular flight, a smaller range can be chosen. For example, the instrument that flew on STS-4 was limited to a maximum mass of about 70.

There is some advantage in choosing a smaller mass range if there is no need for the larger range. As described in Section 2.3.9 on programming the

spectrometer, the voltage that controls the mass is supplied by a 10-bit digital-to-analog (D/A) converter. If the 1024 steps available from the D/A need cover only 0-70 amu instead of 0-150, there are twice as many steps devoted to each mass. It is then easier to select the single step that best represents the top of each mass peak.

The resolution of the mass spectrometer refers to its ability to separate adjacent masses. A precise definition of resolution is $M/\Delta M$, where M is the mass and ΔM is the width of the peak appearing at mass M. The width is measured at a specified peak height; we use the width at 10% of the height. In practice, if a mass spectrometer has a resolution of 50 using a 10% peak height criterion, then that instrument could just distinguish between ions of mass 50 and 51 if one of them had 10% the intensity of the other.

The resolution of the QINMS instruments is easily adjustable during testing and calibration of the instrument, but cannot be changed during the flight. Table 1 lists the resolution range as $M/\Delta M = 30\text{-}50$. QINMS is capable of higher resolution than 50. However, there is a tradeoff between resolution and signal intensity: higher resolution comes only at the expense of lower signals. The range of resolution listed in Table 1 represents a good compromise between the two, and is the sort of resolution usually used for our flights.

The quadrupole mass filter primarily acts as a band-pass filter, allowing only ions within a certain range to get through. The resolution controls the width of the band. The quadrupole rods can also be used as a high-pass filter, allowing all ions with mass greater than some threshold mass to get through. The threshold mass is adjustable, and can be programmed in the same way as the mass. QINMS can be programmed to switch between the band-pass and the high-pass modes of operation as frequently as needed. The high-pass mode is also called the total ion mode, because it gives a measure of the total ion intensity above the threshold.

The five decade dynamic range for the mass spectrometer signal is set by the design of the logarithmic amplifier. As described in Section 2.3.6, this range could be increased if there were no requirements for fast response times. A range of five decades has proven to be a good match between the sampling speed requirements and the range of the electron multiplier.

The sensitivity of the instrument, which gives the correspondence between the measured currents and actual species concentrations, is derived from laboratory calibration measurements. This procedure is discussed below.

The spatial resolution of the data points refers to the distance the instrument has traveled through space between successive mass measurements. This parameter is important in determining the ability of the instrument to observe the spatial structure of variations in composition or density. The orbital velocity at

300 km altitude is ~ 8 km/sec. So, at a sampling speed of 100 Hz, the instrument takes one measurement every 80 m. Unless the instrument is programmed to measure the same species several times in a row, however, the spatial resolution of any given constituent of the atmosphere will be lower than 80 m. The density/pressure grid can be sampled as fast as once every 1/1000 sec. This gives a spatial resolution for this measurement of 8 m.

The fastest rate at which the instrument should be switched between the ion mode and the neutral mode is once per minute. In the present design of the ion source electronics, the filament current is turned off when the instrument operates in the ion mode. Though the mass spectrometer could switch modes much faster than once per minute, the life of the filament might be reduced by more frequent switching. We are presently designing a new ion source in which the filament is left on constantly and where the beam of electrons across the source is turned on an off with electrostatic potentials on appropriate source elements. This new design will permit much faster mode switching.

2.3 Detailed Design Description

This section contains a description of the physical layout of QINMS and presents details on several of the important components of the spectrometer. Only those components whose function is important to the users of the instruments are included. Other AFGL Technical Reports[20,21] contain additional information on other electronic components.

2.3.1 GENERAL DESCRIPTION

Figure 1 is a photograph of the QINMS instrument as it was flown on STS-4, Figure 2 is a schematic drawing of the interior construction of the instrument, and Figure 3 is a block diagram of the electronics. As these figures show, the mass spectrometer consists of two separate packages. The sensor package is divided into an evacuated section above the mounting flange and a sealed section below the flange. The evacuated section contains an electron impact ion source, an ion focusing grid system, the quadrupole rods, and the electron multiplier. This part of the sensor is sealed by a motor driven cover. The cover is closed during all operations on the ground, and is commanded to open once the Shuttle reaches its orbital altitude. The cover is closed again before reentry. The rectangular box below the flange, which is hermetically sealed and filled with dry

20. Trzcinski, E. (1980) Instrumentation Development for LASSII Equatorial Measurements, AFGL-TR-80-0150, AD A088880.
21. Murphy, G.P. (1979) The Design of Mass Spectrometer Assemblies for Space Shuttle Launched Satellites, AFGL-TR-79-0233, AD A080439.

nitrogen to 1 atm, contains the rf oscillator, two logarithmic data amplifiers, and the high voltage power supply to bias the electron multiplier. The second of the two separate packages is the electronics box containing all the command, program, signal conditioning, and telemetry circuitry as well as the low voltage dc/dc converter that powers the instrument. The sizes and weights of the two packages are listed in Table 2.

Table 2. QINMS Physical Parameters

Package	Size (in.)	Weight (lb)
Sensor	$7.38 \times 5.75 \times 15.38$	23
Electronics	$6.62 \times 6.46 \times 6.00$	6

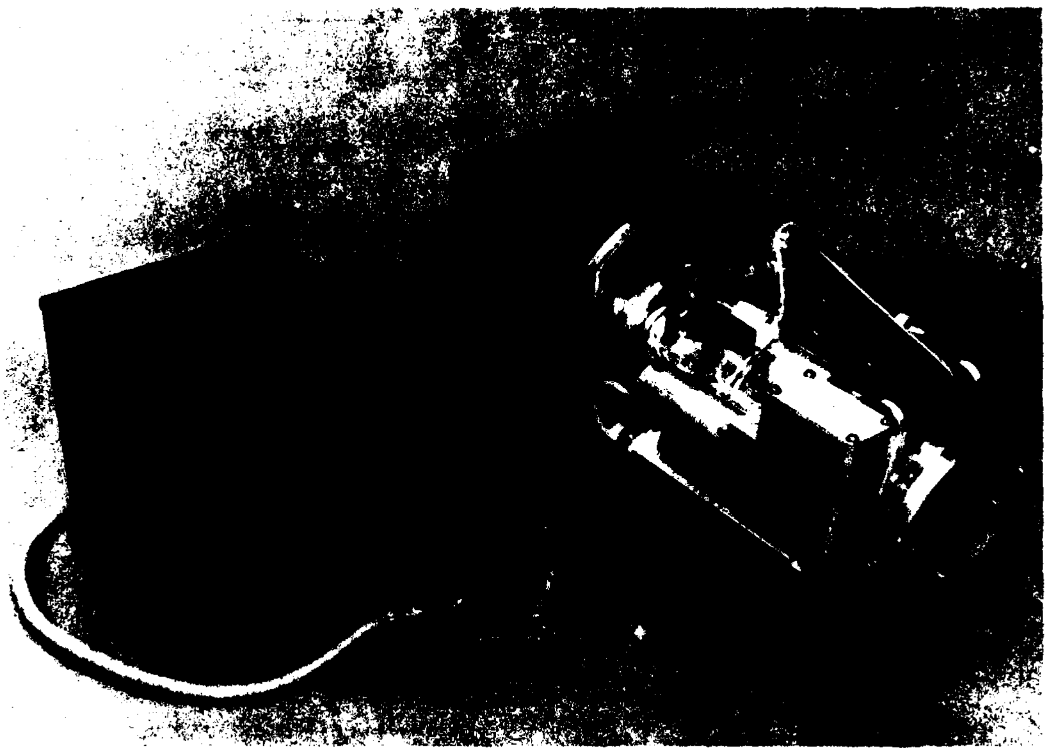

Figure 1. Photograph of the QINMS Instrument

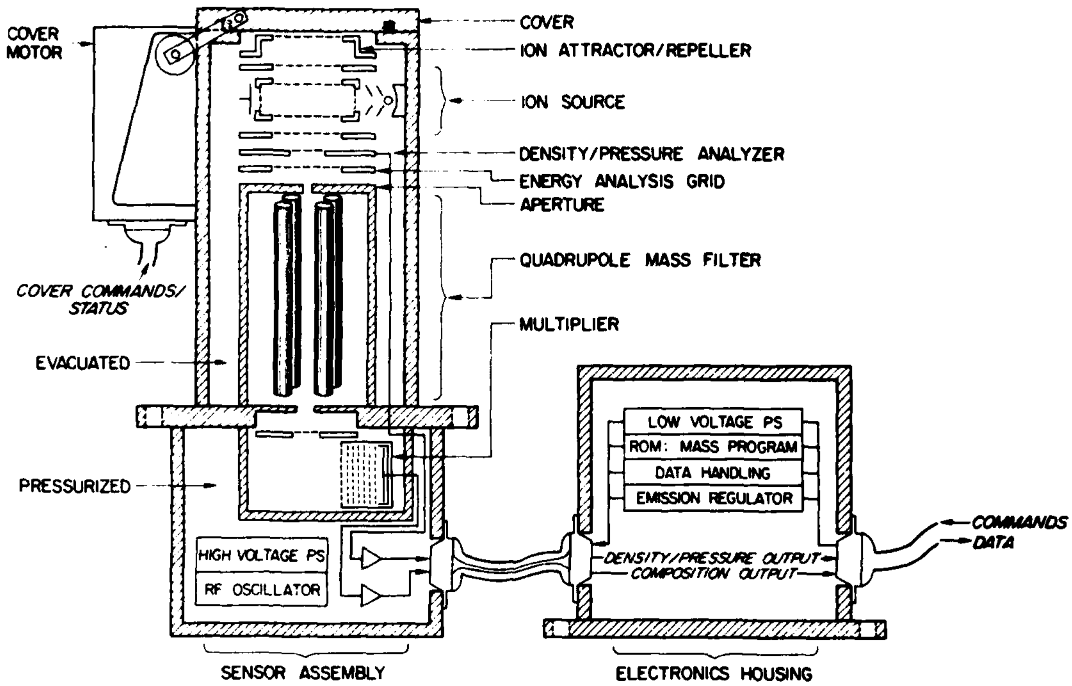

Figure 2. Schematic Diagram of Internal Construction of QINMS

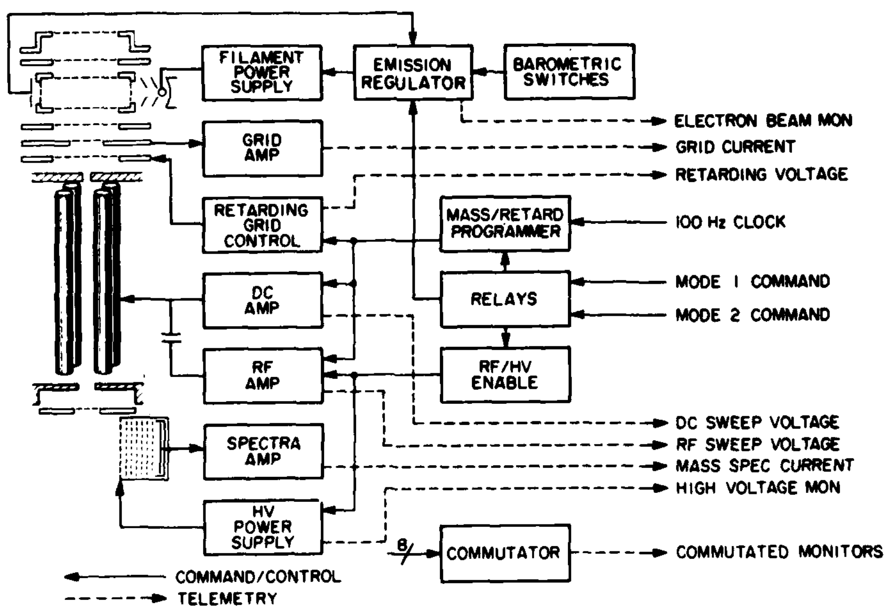

Figure 3. Block Diagram of QINMS Electronics

2.3.2 ION SOURCE

A scale drawing of the ion source assembly is shown in Figure 4. The ion source consists of a stack of gold plated grids mounted on insulating supports. Each grid is made of 70 mesh, 90% transmittance gold screen spot welded to a stainless steel plate. The size of the aperture in each plate varies as shown in the figure. The spacing between the grids is 0.040 in.

The filament is mounted on the side of the source box. The transverse electron beam that it produces is controlled by five electrodes: the repeller behind the filament, two focusing electrodes between the filament and the source box, the source box itself, and finally the anode on the far side of the box. Apertures on the sides of the box limit the size of the electron beam to 0.85 in. wide by 0.20 in. thick, though the beam itself is probably somewhat smaller.

The electron current collected on the anode is monitored by the ion source electronic circuits and is used to regulate the intensity of the electron beam to within ± 2% of the set value. The intensity of the beam is generally about 50-75 μA and the energy is usually in the range 90-120 eV.

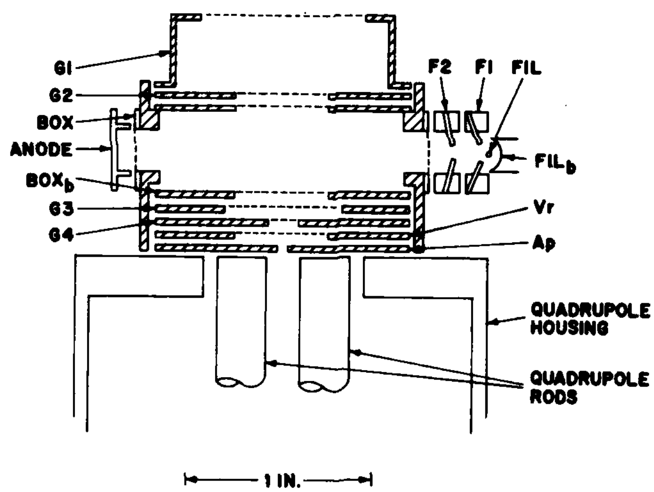

Figure 4. Scale Drawing of the Ion Source

The potentials placed on each of the elements of the ion source in both the neutral and the ion mode of operation are listed in Table 3. The top grid, G1, is exposed to the environment as soon as the cover is opened. In the ion mode, the attractive -10 V potential draws ambient ions into the instrument. In the neutral mode, the ambient ions are repelled by the +10 V potential. The electron repeller grid, G2, is biased at -10 V in both modes to prevent ambient electrons from entering the ion source. The ion source box is biased at -10 V in the ion mode to maintain the energy of the ions passing through the ion source, and at ground in the neutral mode. The bottom plate, Box b, of the ion source is slightly more attractive to the positive ions in both modes to draw the ions out of the source. The next grid below the box, G3, is electrically tied to the repeller behind the filament to prevent electrons from the filament from reaching the lower parts of the source assembly.

The next grid, G4, is the pressure/density analyzer. It is held at -10 V in both modes of operation in order to assure good collection of the ions, and has a relatively small aperture to collect a substantial fraction of the ion current.

The retarding potential analyzer grid lies below the density/pressure grid, and is biased in accordance with the mass program to accomplish the several types of energy analysis experiments described above. The ion source drawn in Figure 4 shows the configuration that was flown on STS-4. Since then, an additional grid has been installed between the pressure/density grid and the Vr grid to reduce the capacitive coupling between the two. This grid is biased at -10 V in both modes.

For both ion and neutral operation, the aperture plate, Ap, is held at -15 V. This potential defines the entrance energy of the ions into the quadrupole itself. Ions derived from neutrals in the ion source pass through the quadrupole at 15 eV, whereas ambient ions may have slightly higher energy due to their initial kinetic energy with respect to the Shuttle. The transmission energy of the ions through the quadrupole rods is important in controlling the performance of the spectrometer.

The filament and the electron focusing elements are held at approximately the same potential as the other elements in the ion mode so as not to disturb the trajectories of the ions. In the neutral mode, the potentials are set to form the electrons into a beam at an energy of ~ 100 eV.

The geometry of the source gives a 20° half angle acceptance cone for unimpeded passage of species into the sampling aperture. Because ions lose their charge when they contact the metallic surfaces of the source, this 20° cone probably defines the real sampling volume for the ion mode. Neutrals, however, do not necessarily react with the ion source electrodes. The sampling volume for stable neutrals, then, may be defined by a 2π sr field of view.

Table 3. Ion Source Potentials

Element	Potential	
	Ion Mode (V)	Neutral Mode (V)
G1	-10	+10
G2	-10	-10
Box	-10	0
Box b	-12	-2
G3	-15	-124
G4	-10	-10
Vr	variable	variable
Ap	-15	-15
Fil b	-15	-124
Fil	-13	-120
F1	-12	-116
F2	-4	-45
Anode	0	+24

The ion sources used in the STS-4 flight instrument and the instrument on the AFP-675 flight had the type of electrostatic focusing and confinement of the electron beam described above. More recent instruments use magnetic confinement of the electron beam. The focusing elements F1 and F2 are removed, the grids at the entrance and exit planes of the beam into the ionization box are replaced with slits, and small permanent magnets are installed behind the filament repeller and the anode. The magnetic field produced by the magnets is parallel to the electron beam direction, and forces the electrons to move in helical paths along the field lines. Magnetic confinement and focusing of the electron beam gives more stable and reliable ion source operation.

2.3.3 QUADRUPOLE RODS

The quadrupole rods are made of 1/4 in. diam. stainless steel and are slightly less than 9 in. long. Both the rods and their alumina mounts are ground to 0.0005 in. tolerances. The quadrupole assembly is housed within a stainless steel cylinder inside the primary instrument housing. The additional housing shields the ion source region from rf interference. Slits are cut in the side of the inner cylinder to permit pumping.

2.3.4 ELECTRON MULTIPLIER

QINMS detects the ions that come through the quadrupole rods with a Johnson Model MM1-5NG discrete dynode electron multiplier. Figure 2 shows that it is mounted off the quadrupole axis and perpendicular to it. This common arrangement prevents light or energetic neutral particles from causing a background current.

The neutral pressures and ion densities in the Shuttle environment are high enough to use the multiplier in the analog, current amplification mode rather than in pulse counting mode. Figure 5 is a graph of multiplier gain vs voltage for a typical multiplier. A voltage of about 2500 V is generally sufficient, though higher voltages can give greater sensitivity if the need arises. As always, there is a tradeoff. At higher gain, the lifetime of the multiplier is reduced, and noise is increased.

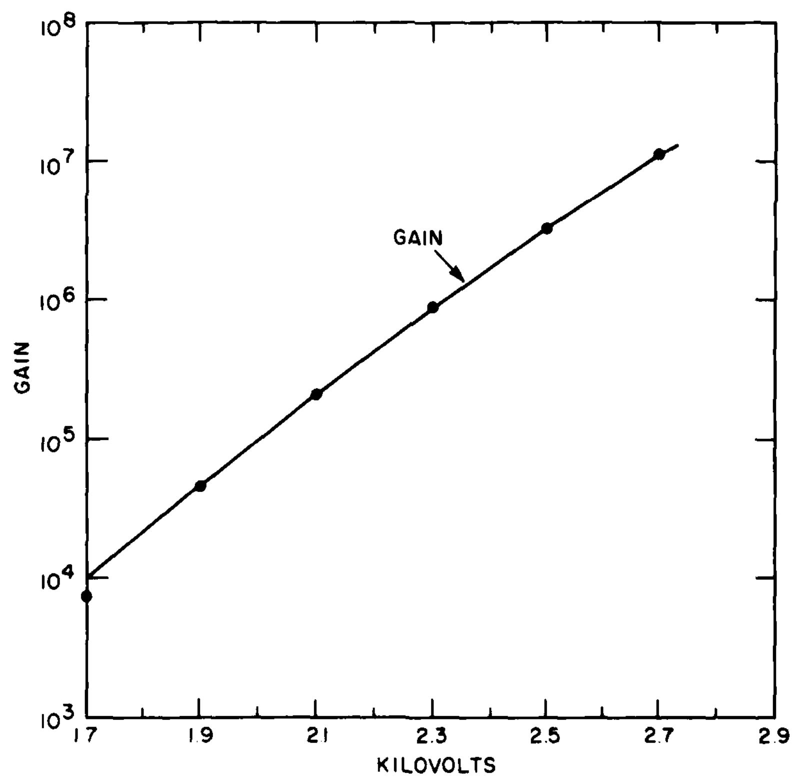

Figure 5. Gain vs Multiplier Voltage for Johnson Multiplier

One significant advantage of the Johnson multipliers is that they can be refurbished at the factory. In addition, they are more stable when used as analog amplifiers than other types. For certain applications, it may be possible to install Channeltron continuous dynode multipliers in the QINMS instruments. Possible advantages of these are higher gain and better pulse counting characteristics.

2.3.5 COVER

The evacuated part of the sensor package is sealed by a motor driven cover. The O-ring seal is recessed into the cover and seals against the front plate of the quadrupole housing. The cover is held in place by two arms, and is driven through a gear box by a TRW Globe motor (Type LL planetary gear motor). The cover is spring loaded against the two arms so that the cover is open the maximum amount at all times during cover opening. The cover requires ~ 12 sec to move completely from the closed to the open position.

The cover position is monitored by two microswitches, one at each end of its motion. The outputs from these switches are available in the telemetry from the instrument. Only the completely open and the completely closed cover positions are monitored. If both microswitches are open, it can only be determined that the cover is somewhere between the two end points.

A schematic of the cover control circuits appears in Figure 6. The cover is controlled by two sets of commands: Cover Power On/Off and Cover Select Open/Closed. Both commands activate non-latching relays and must be held for the duration of the cover motion. The cover power line is interrupted by a relay that is controlled by the cover direction commands. Hence, both a cover direction command and the Cover Power On command must be activated together before the cover can move. The cover direction commands control a polarity reversal relay network. Power must be available to the cover independently of the QINMS Power On command so that the cover can be opened on orbit before the instrument is turned on.

A small valve (Cryolab Model SV1-82-5S2) is located in the center of the cover. The valve consists of a cylindrical tube into which a threaded plug is inserted. The plug has an O-ring that seals against an inner surface of the cylindrical tube. A removable valve operator assembly seals to the outside of the tube. This assembly contains a handle for the plug and also serves to connect the valve to other vacuum equipment. This valve is used to pump out the sensor with the portable vacuum stand and to attach the ion pump to the sensor. Both of these pieces of ground support equipment are described in Chapter 4.

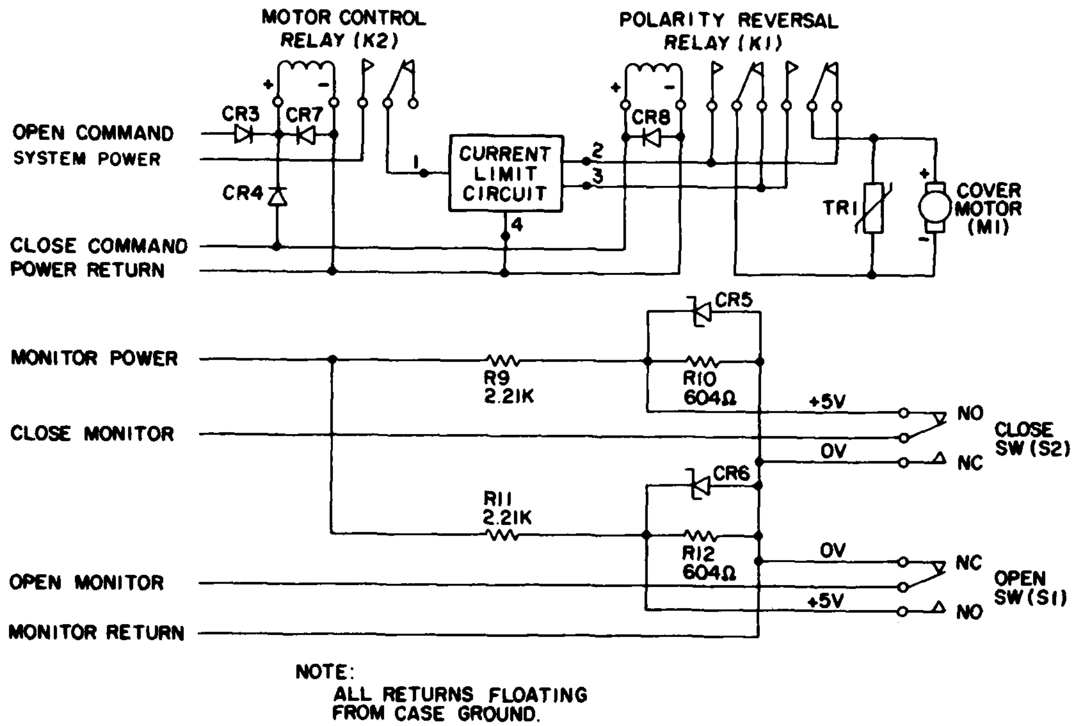

Figure 6. Schematic of Cover Control Logic and Telemetry

2.3.6 LOGARITHMIC AMPLIFIERS

Both types of scientific data from the QINMS instrument, the pressure/density monitor and the electron multiplier signal, are originally currents in the 10^{-11} to 10^{-6} amp range. These currents are converted to telemetry volts by two logarithmic amplifiers. The conversion between current and volts is 1 V per decade of current. Thus, the 0-5 V output range of the amplifiers corresponds to a five order of magnitude dynamic range in current. The lowest detectable current is 5×10^{-11} amp, and the amplifiers are limited at 5×10^{-6} amp. A block diagram of the logarithmic amplifiers appears in Figure 7.

One minor limitation of the amplifier design is the dependence of response time on the input current. The response time increases as the current drops, thus making fast measurements of very low currents difficult. The lowest detectable current is established by a threshold or zero-point current that is added to the input signal. This threshold current maintains the response time at an acceptable level. It is possible to increase the sensitivity of the instrument by lowering this threshold current, though only at the expense of the response time.

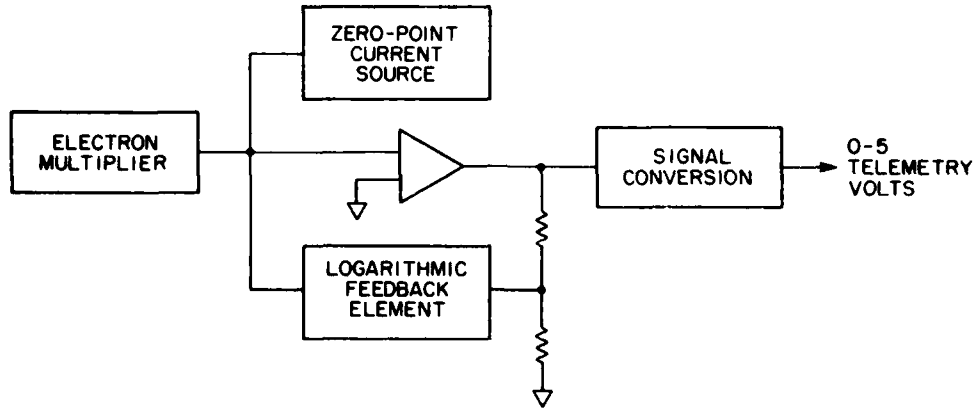

Figure 7. Block Diagram of Logarithmic Amplifiers

2.3.7 POWER SUPPLIES

A block diagram of the power distribution system within the QINMS instrument is shown in Figure 8. Power is supplied to QINMS by the spacecraft according to the specifications discussed in Section 3.1. The +28 V unregulated power is reduced to +20 V by a pre-regulator and then is converted to a variety of voltages by the dc/dc converter. The dc/dc converters usually operate between 25 and 30 kHz. The power return ground is separate from the signal and system ground.

The first time the instrument is turned on in flight, the QINMS Power On command (see Section 3.3) activates only the low voltage dc circuits. The high voltage, rf, and emission regulator circuits are enabled by a latching relay that is switched to the on position by the first Ion Mode command sent to the instrument. Since there is no way to switch this relay back to the off position in flight, the high voltage circuits remain enabled throughout the flight and are then controlled by the QINMS Power On/Off commands.

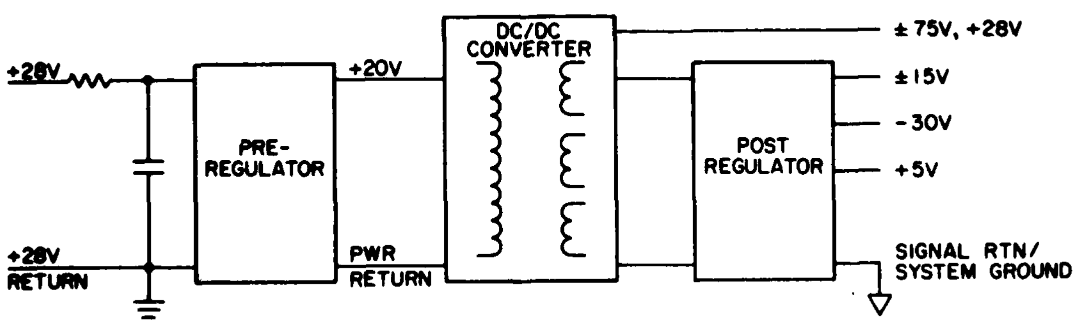

Figure 8. Block Diagram of Power Distribution System

2.3.8 EMISSION REGULATOR

A block diagram of the emission regulator circuit is shown in Figure 9. The current through the filament, and, in turn, the amount of electron current emitted by the filament, is controlled by the filament power supply. The anode on the far side of the source box (see Section 2.3.2) collects a certain, constant fraction of the emitted electrons. This anode current is sensed by the current regulator. Whenever changes in the anode current are detected, the current regulator compensates by changing the filament drive voltage appropriately.

The amount of anode current that the current regulator is supposed to maintain is set by a potentiometer in the current regulator circuit, and so can be changed easily during the setup of the instrument. The voltage of the anode is governed by a Zener diode, also in the current regulator. This diode cannot be changed as easily. The energy of the electron beam inside the ion source is controlled by the potentials placed on the ion source electrodes and by the filament bias power supply.

The filament drive is referenced to the power return ground, whereas the current regulator is referenced to signal ground. The two grounds are separated by the opto-isolator.

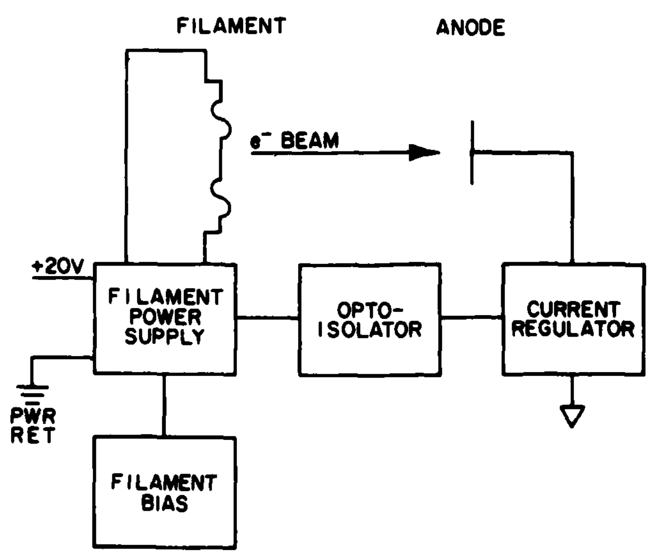

Figure 9. Block Diagram of Emission Regulator

2.3.9 PROGRAMMING CIRCUITRY

The only control of the QINMS instrument that is available during the flight, other than the cover commands and the power on/off commands, is provided by the two operating mode commands: Ion Mode and Neutral Mode. (We also use the names Mode 1 for ion mode and Mode 2 for neutral mode.) These two commands select whether the instrument is sensitive to ions or to neutrals and activate the measurement sequence appropriate for that mode. All other information required by the instrument to carry out the experiments must be stored internally before the flight.

This prerecorded information is stored as a sequence of numbers in Erasable Programmable Read-Only Memories, or EPROMs. The primary instrument function, controlled by the sequence of numbers, determines the mass of the species that will be allowed to pass through the quadrupole mass filter. For this reason, the entire sequence is referred to as the "mass program". The voltage placed on the retarding potential analyzer is also controlled through the programming circuitry.

The block diagram in Figure 10 shows the essential elements of the programming circuitry. Both of the EPROMs have memory available for 512 words; each word, therefore, requires a 9-bit address. The eight least significant bits of the 9-bit address are supplied by the binary counter. At each clock pulse, the counter advances to the next higher address, and recycles to 0 after 255. The most significant bit is provided by the mode commands. The mode control line is 0 in Mode 1 (ion mode) and 1 in Mode 2 (neutral mode). (Of course, the mode commands also control other instrument functions such as the filament power supply, the emission regulator, and the potentials placed on the electrodes of the ion source.) The effect of this arrangement is to divide the 512-word EPROMs into two halves. In the ion mode, the EPROMs cycle through steps 0 to 255, and in the neutral mode, the program has access to steps 256 through 511. Thus, each operating mode has its own 256-step mass program.

The clock that advances the counter is not internal to the QINMS instrument, but must be provided by the host vehicle that carries the mass spectrometer into space. The frequency of the clock can be chosen to synchronize QINMS to the data storage or telemetry system of the spacecraft, if necessary. The upper limit of the clock frequency is 100 Hz, a limitation that stems from the response time of the logarithmic amplifiers. There is no lower limit to the clock frequency, though nothing is gained by running the instrument more slowly than 25-50 Hz. The counter reset line can also be used to synchronize the mass spectrometer data stream to the telemetry system.

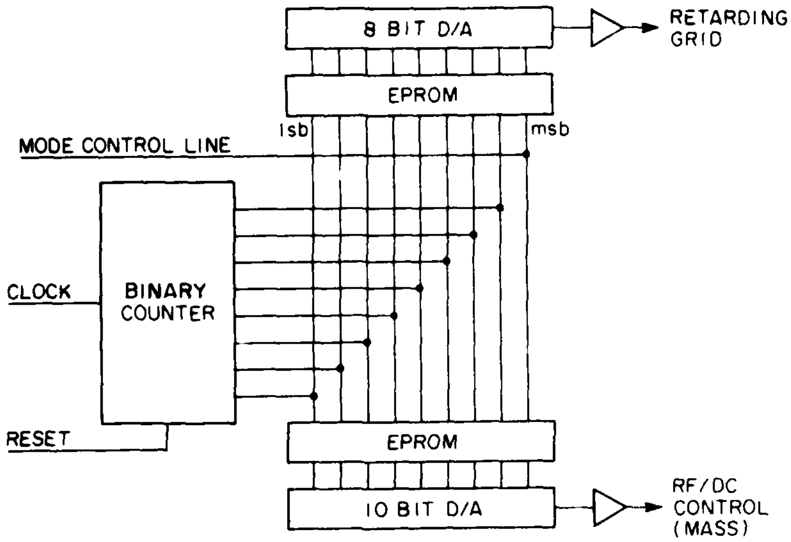

Figure 10. Block Diagram of Programming Circuitry

Each of the two EPROMs takes the address supplied to it by the counter, looks up the number that is stored in that address, and puts that number onto the output lines in binary format. These numbers are converted to actual voltages by digital-to-analog (D/A) converters, and are then conditioned by appropriate amplifiers. The resolution of the voltage steps depends on the number of bits in the EPROM data. The 10-bit D/A converter for mass control gives a total of 1024 steps, whereas the 8-bit D/A converter for retarding potential allows only 256 steps. The higher resolution was chosen for mass control so that each mass peak would be covered by several steps.

In the laboratory, the mass control voltage can be stepped from 0 to 1023 sequentially, giving a nearly continuous mass scan. Such scans are useful for adjusting the resolution and for checking the shapes of the peaks, but use data collection time inefficiently during a flight. The flight EPROMs are programmed to measure the intensity of each mass at the single voltage closest to the top of the mass peak. (In some cases, we have programmed the flight EPROMs to look each voltage across the top of a single peak to make sure that the peak is not drifting during the flight.)

Because the two EPROMs receive their addresses from the same counter, the two sets of instructions are always synchronized with each other. Other than this, however, the two EPROMs can be programmed completely independently. In practice, the two programming capabilities are not really used simultaneously; either the mass is scanned while Vr is held constant, or vice versa.

The description given above applies to the instrument as it was flown on STS-4. Several modifications are possible to increase the versatility of the programming. The number of independently commandable programs can be increased by controlling more of the high order bits of the address directly from telemetry commands rather than from the counter. This involves adding more relays to the command electronics, and, of course, requires that the spacecraft command structure be modified to supply the extra commands. In addition to this modification, the choice of operating in ion or neutral mode can come from an extra output bit in the rf/dc EPROM rather than from the commands. In this way, the instrument, in principle, could be switched from ion to neutral mode operation every time the clock advances the address; in practice, though, the filament could not respond that fast. However, this capability would allow each separately commanded mass program to be either an ion mode or a neutral mode program, eliminating the need for the entire first half of memory to belong to ion mode and the second half to neutral mode.

2.3.10 COMMAND/TELEMETRY CIRCUITRY

Typical command input and telemetry output circuits are shown in Figure 11. Commands are sent to the instrument through either latching or non-latching relays (see Section 3.3). Commands are usually paired so that one command sets the relay and the other command resets it. The command return is isolated from both the power return and the signal return.

Most of the telemetry from the instrument is analog (see Section 3.5) and is provided from operational amplifiers. The output impedance of the telemetry circuit is typically less than 1-K ohm. The telemetry circuits are referenced to the system ground.

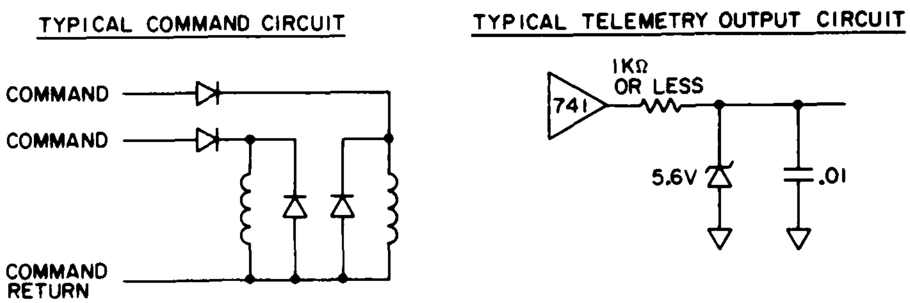

Figure 11. Typical Command and Telemetry Circuits

2.3.11 CONNECTORS/PIN ASSIGNMENTS

The seven external connectors, J6-J12, on QINMS are listed in Table 4 along with the type, location, and function of each. (J1-J5 are the PC board edge connectors inside the electronics box.) The location of the other end of the cable attached to each connector is also given. Section 4.2.2 has considerably more information on the configuration of the cables that attach to these connectors. Only J8, J9, and J11 connect directly to the spacecraft. Pin assignments for these three connectors are shown in Figure 12.

Table 4. QINMS Connectors (Flight Configuration)

Number	Type*	Location	Connected To	Function
J1-J5	-	Inside Electronics Box	-	Internal Connections
J6	DB-25S	Electronics Box	Sensor J10	Instrument Functions
J7	DB-25P	Electronics Box	Jumper Connector**	Interlock Jumpers
J8	DA-15S	Electronics Box	Spacecraft	Telemetry
J9	DA-15P	Electronics Box	Spacecraft	Commands/Power
J10	DB-25P	Sensor	Electronics Box J6	Instrument Functions
J11	DE-9P	Cover Logic Box	Spacecraft	Cover CMD/TLM/Power
J12	DE-9S	Cover Logic Box	Cover Motor	Cover Motor Power

*All are Cannon Connectors

**J7 is connected to the Control Console during ground testing, and then carries power, commands, and telemetry (see Section 4.2.2).

J8

Pin	Assignment
1	GROUND
2	–
3	APERTURE AMP
4	–
5	SPECTRA AMP
6	–
7	RF MON
8	HV MON
9	DC MON
10	ER MON
11	VR MON
12	COMMUTATOR
13	–
14	100 Hz CLOCK
15	–

J9

Pin	Assignment
1	POWER RETURN
2	POWER RETURN
3	–
4	QINMS POWER (+28V)
5	QINMS POWER (+28V)
6	–
7	MODE 1
8	–
9	MODE 2
10	–
11	–
12	–
13	–
14	–
15	COMMAND RETURN

J11

Pin	Assignment
1	COVER POWER (+28V)
2	SELECT COVER OPEN
3	–
4	COVER MONITOR POWER (+28V)
5	COVER POWER RETURN
6	SELECT COVER CLOSED
7	COVER OPEN MON
8	COVER CLOSED MON
9	MONITOR POWER RETURN

Figure 12. Pin Assignments for Selected QINMS Connectors

3. INTEGRATION REQUIREMENTS

This chapter describes the orbital environment in which the QINMS instrument can operate safely. It also presents the requirements for the power, command, and telemetry interfaces between the instrument and the spacecraft. A brief summary of the integration requirements is given in Table 5, and a more detailed description is given in the text.

3.1 Power

The QINMS instrument requires nominal +28 V unregulated power from the spacecraft power system. The voltage regulator inside QINMS can accept voltages between 24 and 40 V and still maintain regulation. Voltage spikes or drops should stay in this range regardless of their duration. A dc/dc converter within the instrument transforms this input power to the voltages required by the internal circuitry. The frequency of the dc/dc converter varies from instrument to instrument, but is usually between 25 and 30 kHz.

Table 5. Integration Requirements

Power/Voltage	Input Voltage	+28 V ± 4 V Unregulated
	Average Power	15 W Ion Mode 18 W Neutral Mode
	Peak Power	16 W Ion Mode 20 W Neutral Mode
	Cover Power	25 W for 25 sec
Environment	Temperature	0° to 50°C, Operation -25° to +125°C Storage
	Operating Pressure	$< 1 \times 10^{-4}$ Torr
Commands	Type	+28 V Discrete Relay Drivers
	Total Number	8
Telemetry	Discrete Monitors	2
	Analog Monitors	8
	Serial Digital Monitors	0
	Total Bit Rate	11,226 bps (max)

The amount of power drawn by the mass spectrometer depends on the operation mode and the mass of the species being observed. The ion source circuits and the filament must be turned on during neutral mode operation. These increase the power usage by about 3 W. Both the dc and the rf voltage supplied to the quadrupole rods, and thus the power dissipation, must increase when higher masses are to be passed through the mass filter. The values for peak and average power in each of the two operating modes given in Table 5 represent, respectively, the power at the highest mass the instrument can measure and the average of that value with the power at the lowest mass. These values are approximate; the actual values for any given instrument depend on the highest mass measured and on the mass program chosen.

3.2 Environment

3.2.1 TEMPERATURE

The electronics are designed to operate properly and to stay within calibration between 0° and 50°C. The instrument will not be damaged if it is operated between -10° and 70°C; however, the calibration may be so adversely affected that the data may be uninterpretable outside the proper operating range. Whenever the instrument is turned off, as in storage or transportation, the temperature may range from -25° to +125°C without damage to the electronics.

No control of the thermal environment is provided by QINMS. The design of the thermal control hardware and the installation of heaters and thermal blankets must be part of the overall satellite design and integration process.

3.2.2 PRESSURE

Mass spectrometers can operate only at low pressures. At high pressures, collisions between the ions of interest and background molecules alter the trajectories of the ions through the instrument, and, therefore, reduce the ability of the instrument to separate masses and reduce the overall signal. In addition, most mass spectrometers require high voltages on some of their components; arcing can occur at certain critical pressures.

QINMS is typical of mass spectrometers in requiring a pressure below 5×10^{-5} Torr in the evacuated part of the sensor for safe, continuous operation. Occasional bursts of gas up to 1×10^{-4} Torr may be acceptable. QINMS provides no pumping of the sensor, so the instrument can only operate in an environment where the ambient pressure is below 5×10^{-5} Torr. The instrument is equipped with a barometric safety interlock switch that prevents filament operation below pressure equivalent to 50,000-ft altitude. However, this switch cannot turn the instrument off to prevent arcing or performance degradation in the event of momentary high pressure.

Ambient species travel at high velocity with respect to the mass spectrometer when the instrument is mounted on a satellite or rocket. The flow of these species into the ion source creates a higher than ambient pressure in that region. This ram pressure enhancement, as it is called, can be as large as a factor of 100 for satellites in low earth orbit. The ambient pressure at 180 km is $\sim 1 \times 10^{-6}$ Torr. Multiplying this pressure by the ram enhancement factor gives the upper limit for the ion source pressure. Thus, QINMS should not be operated for long periods at altitudes lower than 180 km.

The pressure of contaminant species in the ion source does not have as large an angle of attack dependence as the ambient species. The instrument has successfully operated in the Space Shuttle payload bay environment, and measured the effects of such contamination events as thruster firings and water dumps. It is conceivable, though, that combining contamination events with a bay-to-ram attitude of the shuttle might give a total ion source pressure greater than the safe upper limit pressure.

3.2.3 OTHER ENVIRONMENTAL CONSIDERATIONS

3.2.3.1 Fields and EMI

QINMS is sensitive to electric and magnetic fields near the cover and the entrance to the ion source in that the motions of ions entering the instrument will be affected by the fields. A magnetic field of > 1 G or an electric field greater than a few V/cm in front of the instrument is considered too large. QINMS should be positioned on the spacecraft as far from the sources of such extraneous fields as possible. Electric and magnetic fields have no effect on the operation of the instrument in neutral mode unless they are extremely large. QINMS passed all Shuttle requirements for production of EMI for the STS-4 flight, and is expected to pass for all future flights.

3.2.3.2 Gases and Particulates

During normal operation, QINMS produces no gaseous contaminants other than those desorbed from the surfaces of the instrument through normal degassing. As described in Section 2.3.1, part of the electronics is hermetically sealed and filled with dry nitrogen to a pressure of 1 atm. If this compartment developed a leak, minute amounts of nitrogen would be released into the environment. QINMS emits no particulates.

The instrument is sensitive to the release of gaseous contaminants by other spacecraft systems or experiments in that these releases have an effect on the measurements. So long as the total pressure due to these releases remains below the maximum pressure discussed above, there are no safety related restrictions on the release of such contaminants. However, from a scientific viewpoint, restricting the releases to specified times may be desirable for certain experiments.

3.3 Commands

QINMS requires a total of eight commands. These can be categorized as power, cover, and mode commands, and are listed in Table 6. Each of the commands is a discrete +28 V signal. There are no serial digital commands. Some of the commands control non-latching relays and so must be applied to the instrument for the duration of the command operation. Others control latching relays that require pulsed +28 V signals. Specifications for the commands are listed in Table 7.

This section describes only the function of each of the individual commands. The combination of the commands into command sequences and their use in flight are described in Chapter 5.

Table 6. Command List

Power Commands	QINMS Power On
	QINMS Power Off
Cover Commands	Cover Select Open
	Cover Select Closed
	Cover Power On
	Cover Power Off
Mode Commands	Mode 1 (Ion Mode)
	Mode 2 (Neutral Mode)

Table 7. Command Specifications

Command Type	Discrete High Level
Voltage	+28 V
Momentary Commands	
Pulse Width (min)	20 msec
Pulse Width (max)	n/a
Rise Time	n/a
Maximum Current	100 mA
Continuous Commands	
Maximum Current	120 mA

3.3.1 POWER COMMANDS

QINMS requires +28 V power lines from the host spacecraft, as described in Section 3.1. The QINMS Power On and QINMS Power Off commands must simply apply or remove the power from these lines, respectively. The design of the circuits that accomplish this, which are external to the QINMS instrument, is at the discretion of the integrating contractor.

3.3.2 COVER COMMANDS

The cover requires four commands. Cover Select Open and Cover Select Closed determine the direction of the cover motion. Cover Power On and Cover Power Off actually operate the cover motor. Both types of commands operate non-latching relays. Therefore, the command circuits on the spacecraft side of the interface must be able to provide +28 V on the appropriate lines for the duration of the command operation. Section 2.3.5 has more information on cover commands.

3.3.3 MODE COMMANDS

The two mode commands, Mode 1 or Ion Mode and Mode 2 or Neutral Mode, switch the instrument between conditions for measuring the ions in the region outside the instrument and those for sampling the neutrals. The mode commands are momentary relay drivers that activate latching relays inside the QINMS electronics box. The relays, in turn, turn the ion source on or off, select the proper bias voltages for the electrodes in the ion source, and select the proper sequence of measurements from the programmed EPROM. The programming circuits are described in detail in Section 2.3.9, the ion source potentials in Section 2.3.2, and the electron beam emission regulator in Section 2.3.8.

3.4 Clock Requirements

The QINMS instrument needs a clock from the spacecraft for several separate purposes, though the same clock might be able to satisfy all of these. First, QINMS needs a 0-5 V square wave clocking signal to drive the binary counter in the programming circuits. As described in Section 2.3.10, the frequency of this clock may be determined by the requirements of the spacecraft telemetry and data handling system, but should be in the range of 25-100 Hz. In addition, a slower rate (on the order of 1 Hz) clocking signal from the spacecraft to the instrument may be required in certain applications to synchronize the QINMS mass program to the telemetry data system.

The second requirement for a clock stems from the need to synchronize the QINMS data with other flight data. For example, correlation of the QINMS data with scientific information from other experiments, Shuttle operations data such as thruster firings and Shuttle ephemeris and attitude are an important part of the data reduction process. This clocking requirement could be satisfied simply by putting a Shuttle mission elapsed time (MET) tag into the data stream from the instrument. Other solutions are certainly possible.

3.5 Telemetry

3.5.1 TELEMETRY MONITORS

The health, status, and scientific data from QINMS are carried on eight 0-5 V analog monitors. Cover status is carried on two additional discrete monitors. The identity, type (analog or discrete), and sampling rate of these monitors are listed in Table 8. A description of each is given below.

Table 8. QINMS Telemetry Monitors

Name of Monitor	Type	Sampling Speed
Grid Current	Analog	1000 Hz (optimum)
Mass Spec. Current	Analog	100 Hz*
dc Sweep Voltage	Analog	100 Hz*
rf Sweep Voltage	Analog	100 Hz*
Retarding Voltage	Analog	100 Hz*
High Voltage Monitor	Analog	1 Hz
Electron Beam Monitor	Analog	1 Hz
Commutated Monitors	Analog	1 Hz
Cover Open	Discrete	1 Hz
Cover Closed	Discrete	1 Hz

*100 Hz is maximum rate. Slower rates are possible.

3.5.1.1 Scientific Data

Grid Current: The current collected on the pressure/density grid varies continuously with time, and so can be sampled by the telemetry system as quickly or as slowly as desired. Faster sampling speeds give better temporal and spatial resolution in the data. The grid current was sampled at 100 Hz on STS-4, but will be sampled at 1000 Hz on other flights. The faster rate is desirable if it can be handled by the telemetry system.

In normal operation, the grid current monitor depends on the pressure in the ion source. Any value in the entire 0-5 V range could represent correct data. The actual value varies with orbit altitude, the angle of attack of the instrument, and many other parameters. In flight, a fluctuation of ± 0.1-0.2 V is normal, whereas in the laboratory, the pressure reading should be steadier. Any behavior other than this could indicate a malfunction. For example, a constant reading of 0 or 5 V is abnormal.

Mass Spectrometer Data: The current from the electron multiplier, also a 0-5 V analog signal, changes at the same rate as the external clock that drives the EPROM address counter. At the fastest speed of 100 Hz, the value on this monitor may change every 0.01 sec depending on the mass program. An A/D converter (part of the spacecraft electronics) can sample the mass spectrometer output voltage at any time during this 0.01-sec period. Sampling toward the end

of the period is preferable to give transient signals time to decay. The conversion from mass spectrometer current to actual species concentrations is given in Section 2.2, and is discussed more fully in Section 4.3.

Because the entire sequence of measurements in the mass program appears serially on the same telemetry monitor, a method for identifying which value corresponds to which measurement must be arranged. The status monitors described below specify the condition of the instrument completely at each step of the mass program. For post-flight data analysis, these monitors can be used to synchronize the data to mass program sequence. In addition, it has proven useful in some cases to provide the QINMS instrument with a synchronization signal from the telemetry system. This is nothing more than a reset for the EPROM address counter. The frequency of such a reset signal would depend on the number of measurements in the mass program and on the speed of the external address clock.

As was the case for the grid amplifier signal, the scientific data coming from the mass spectrometer current monitor depends on the sequence of measurements being made, the condition of the environment, the angle of attack, and other similar parameters. Some noise, as much as ± 0.3 V, is normal.

3.5.1.2 Health and Status Monitors

rf and dc Sweep Voltages: Quadrupole mass filters are operated by biasing the rods with both a dc and an rf component of voltage. The rf and dc sweep voltage telemetry points monitor the amplitudes of these voltage components.

The rf frequency is a constant value determined by several factors, including the desired mass range of the mass spectrometer. The amplitudes of the rf and dc components determine the mass of the ions that will have stable trajectories through the mass filter. The two amplitudes vary in such a way that the rf/dc ratio is constant. Either the rf or the dc sweep voltage monitor shows what mass is being sampled by the mass spectrometer. They are both provided for redundancy.

When the mass spectrometer is set to look at a particular mass, the rf and dc voltages have no fluctuation. The pattern of rf and dc voltages observed in telemetry during the flight should be the same sequence as that programmed into the EPROMs before the flight. The rf and dc monitors thus indicate whether the mass program is stepping properly from measurement to measurement. In addition, the rf and dc monitors can be used during post-flight data analysis to determine which values of the mass spectrometer current correspond to which masses.

Retarding Voltage: The retarding voltage telemetry monitor measures the voltage on the retarding potential analyzer (RPA) grid in the ion source. The retarding voltage is controlled by the programming circuitry in much the same way

as the rf and dc voltages are. Thus, the retarding voltage monitor should also show a fixed pattern of values that changes at the same rate as the external EPROM address clock. The 0-5 V range of the telemetry monitor corresponds to the full range of actual volts on the grid.

High Voltage Monitor: The high voltage monitor is an indication of the voltage that biases the electron multiplier. The 0-5 V range of the monitor corresponds approximately to 0-5000 V at the multiplier.

The high voltage power supply is turned on at the beginning of the flight by issuing the first Mode 1 command. Once this has occurred, there is no way to turn the high voltage off other than removing power from the instrument as a whole. Whenever the instrument is turned on, the high voltage monitor should read a constant value throughout the flight. A multiplier bias voltage near 2500 V is commonly chosen; the monitor should be close to 2.5 V throughout the flight, and should not fluctuate.

Electron Beam Monitor: The amount of electron current arriving at the anode on the far side of the ion source from the filament is actively controlled by the emission regulator circuits. The amount of beam current is adjusted before the flight. When the ion source is turned on and the emission regulator is successfully controlling the beam current, the electron beam monitor should read between 4 and 4.2 V. When the source is off, the monitor should read less than 0.2 V.

Looking at the electron beam monitor is the easiest way to tell whether the instrument is operating in the ion or the neutral mode. (Other methods involve looking at the sequence of rf, dc, or retarding voltage values to determine which of the two mass programs is in use.) This monitor can therefore be used to confirm when commands have been successfully received by the instrument. In addition, the electron beam monitor tells whether the filament is intact or whether there are other problems with the ion source.

Commutated Monitors: A number of other instrument functions have been commutated into a single monitor. These functions are:

1. *rf/HV Relay Monitor*
   Indicates whether the rf and HV functions have been enabled.

2. Mode Monitor
   Monitors which mode of operation, ion or neutral, the instrument is in.

3. Temperature Monitor #2
   Monitors the sensor baseplate temperature.

4. Filament Bias
   Monitors the filament bias voltage.
5. Regulator Monitor
   Monitors the output side of the pre-regulated low voltage dc/dc converter.
6. ± 15 V Monitor
   Monitors those regulated voltages that power most of the analog circuits.
7. Temperature Monitor # 1
   Monitors the temperature of the electronics box.
8. -30 V Monitor
   Monitors the regulated power supply voltage for the aperture amplifier.

The value of the commutator changes once every second; each individual function is sampled once every eight seconds. It is impossible to tell which of the eight functions is being displayed if only one value of the commutator is available. However, if the whole pattern of eight can be viewed, it is easy to tell which corresponds to which function.

3.5.1.3 Cover Status Monitors

As described in Section 2.3.5, the position of the cover is monitored with two microswitches, one at each end of the range of cover motion. The cover physically touches the actuator of each switch, so the switches provide direct information on the cover position.

The cover motor control block diagram (Figure 6) shows that the switches simply control 5 V power lines that are connected directly to the telemetry interface. The Cover Open Monitor reads 5 V when the cover is fully open, and 0 V when the cover is not fully open. The Cover Closed Monitor reads 5 V when the cover is fully closed, and 0 V when the cover is not fully closed. If the cover is in an intermediate position, then both monitors read 0 V; there is no way to tell exactly where the cover is, unless it can be seen.

3.5.2 TELEMETRY DATA BIT RATE

The eight analog voltages provided by the QINMS telemetry are generally not suitable for direct transmission to the ground or for storage on tape. They must first be digitized. Eight-bit accuracy in the A/D conversion is sufficient. The total data bit rate for the analog monitors is the sum of the sampling rate for each of the monitors times the number of bits in the A/D converter. For example, if the EPROM external address clock has a 100 Hz frequency and the grid current is being sampled at 1000 Hz, then the total analog bit rate is calculated as follows:

Monitor	Sampling Rate	×	No. of Bits	=	Rate
Grid Current	1000	×	8	=	8000
Mass Spec. Current	100	×	8	=	800
rf Voltage	100	×	8	=	800
dc Voltage	100	×	8	=	800
Retarding Voltage	100	×	8	=	800
High Voltage	1	×	8	=	8
Electron Beam	1	×	8	=	8
Commutator	1	×	8	=	8
				Total =	11,224 bps

The two cover position monitors each take one bit in the data stream and can be sampled once per second. The total discrete data rate is therefore only 2 bps.

The total bit rate is the sum of the analog and the discrete rates, or 11,226 bps. The 100 Hz rate for the external clock is the maximum allowable rate, and the 1000 Hz rate for the grid monitor is probably as fast as data needs to be taken. The rate of 11,226 bps can be considered the maximum data rate for the instrument. As has been mentioned many times above, the data rate can be reduced substantially by lowering the sampling rate of the grid current, by reducing the frequency of the external clock, or both.

3.6 Mechanical Integration

3.6.1 POSITION OF THE MASS SPECTROMETER ON THE SPACECRAFT

The position of the QINMS instrument on the spacecraft will depend on the experiments to be done on a particular flight and on the limitations of the spacecraft itself. However, some general considerations should be applicable to most situations.

Only the position of the sensor package is important. The electronics box can be located anywhere on the spacecraft so long as the length of the cable between J6 and J10 does not exceed 4 ft. Note, however, that it is preferable to place the electronics box close to the sensor so that their temperatures are similar.

The sensor must be mounted so that the cover is free to open. In addition, the front end of the sensor should ideally have a clear view of space. Obstructions in the hemisphere in front of the sampling plane can interfere with the flow of ambient species into the instrument and be the source of contamination.

Finally, for most applications, the QINMS sensor should point into the ram direction (i.e., pointed so that the centerline of the instrument is parallel to the velocity vector). In this orientation, the instrument has its highest sensitivity and is calibrated most accurately. This requirement will usually affect the position chosen for mounting the instrument.

3.6.2 MOUNTING

Both the sensor and the electronics box have mounting flanges with holes that are to be used for attaching the instrument to the spacecraft. The outlines of these mounting flanges with the hole patterns are shown in Figure 13.

The mounting flange for the electronics box is located on the bottom surface of the box. Hence, the electronics box can be mounted directly to a flat plate or similar structure. In contrast, the mounting flange for the sensor is located in the middle of the sensor (see Figures 1 and 2). As a result, the sensor must be mounted to the spacecraft with a special mounting bracket. The design of this mounting bracket has usually been part of the overall integration procedure for each individual spacecraft.

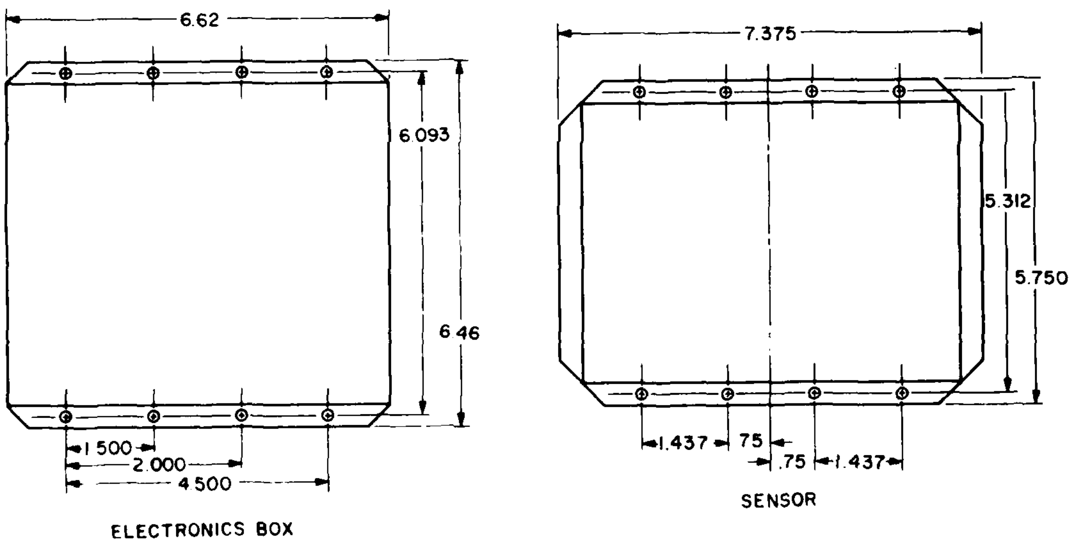

Figure 13. Hole Patterns for QINMS Mounting Flanges

3.6.3 GROUNDING

One of the scientific capabilities of the QINMS instrument is the measurement of vehicle potential. This requires a solid connection to a good spacecraft ground plane. Otherwise, the instrument will measure its own potential rather

than that of the spacecraft. In general, simply mounting the instrument to the metal structure of the spacecraft will satisfy this requirement. However, if the spacecraft is made of non-metallic substances (epoxy-graphite tubes, for instance), then the installation of a specific piece of metal to act as the ground plane may be necessary. The QINMS instrument does not have any exposed high voltages that might cause a perturbation to the vehicle potential.

4. GROUND OPERATIONS

This chapter discusses all of the procedures that occur in the laboratory (at AFGL) and in the field (at the integrating contractor's facilities) before launch of the mass spectrometer. The first section identifies who designs and builds the instruments. The next section is concerned with the pieces of ground support equipment (GSE) required to prepare and test the instrument in the laboratory and in the field, and with the ways in which these pieces of equipment are connected to each other. Finally, the chapter concludes with a discussion of all the testing procedures.

4.1 Design and Construction

The jobs of designing and building the mass spectrometers and their associated GSE are shared between AFGL engineers and contractors. The primary responsibility for the instruments remains with the in-house personnel. Design of the electronics, fabrication of the printed circuit boards, and assembly of the electronics packages are generally done under contract. Design of the mechanical parts of the sensor assembly is done by in-house personnel, whereas fabrication of those parts is done by outside contractors. Final assembly, testing, and calibration of the instrument is done in-house.

4.2 Ground Support Equipment (GSE)

The flight hardware, consisting of the sensor assembly and the electronics package, was described in detail in Chapter 2. Several pieces of additional GSE are needed to operate the mass spectrometer in the laboratory during testing and calibration. A different set of test equipment is required in the field to test the instrument during integration. The first part of this section describes each piece of test equipment individually, and the second shows how they are connected to each other in several different situations.

4.2.1 EQUIPMENT DESCRIPTION

4.2.1.1 Control Console

The control console, shown in Figure 14, is a portable power, command, and telemetry unit built into a suitcase-sized case. It is able to send all flight commands to the instrument (except for the cover commands; see Section 4.2.1.3), and can also send some control functions that are not part of the flight repertoire. The complete list of commands is: Power On/Off, Mode 1/Mode 2, rf On/Off, High Voltage On/Off, and Clock Frequency 100/50/25/6.25/0.75 Hz. The console also allows several safety interlocks, including the barometric switches, to be disabled so that the instrument can be operated on the ground.

The console receives all of the flight telemetry from the instrument and displays the values on 0-5 V meters. The total voltage supplied to the instrument and the current drawn by the instrument are displayed on separate meters.

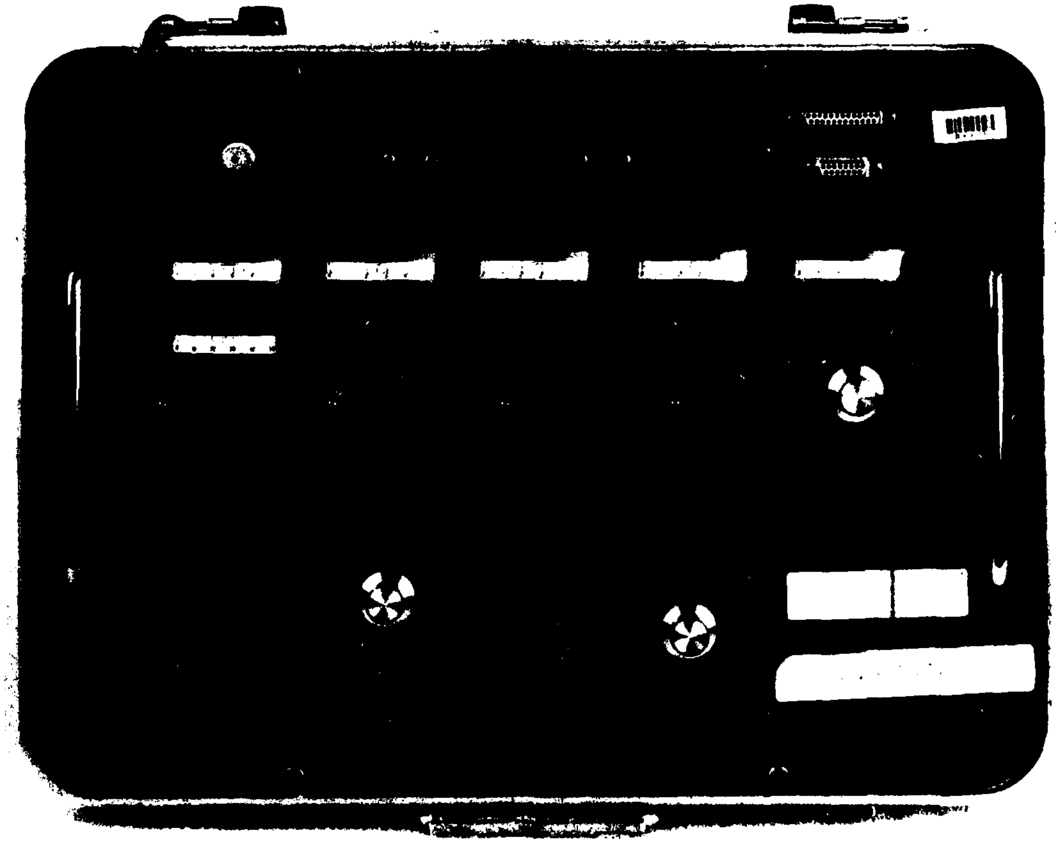

Figure 14 Photograph of Control Console

Finally, the console has output jacks that can be used to connect the telemetry signals to other recording instruments.

4.2.1.2 Chart Recorder

The response time of the meters on the control console is not fast enough to record the changes in the telemetry when the mass spectrometer is cycling through the mass program at flight speed (100 Hz). An oscilloscope could be used to view the information that appears on the output jacks of the control console. A more useful method is to connect the output jacks to a multichannel chart recorder. In this way, a permanent record of several telemetry points can be recorded simultaneously during a test.

4.2.1.3 Cover Actuator

The cover of the mass spectrometer is functionally independent of the rest of the instrument in that its power, commands, and telemetry are carried by a separate interface cable. For this reason, the cover controls were not included in the control console, but were built into a separate unit. The cover actuator provides power to the cover logic and motor, sends the four cover commands, and also displays the outputs from the two cover position microswitches. The cover actuator needs an external (+28 V) power supply.

4.2.1.4 Cover Simulator

The final step in preparing the mass spectrometer for shipment to the integrating contractor is to clean the interior of the instrument by baking the sensor under high vacuum. Once this has been done, it is very undesirable to open the sensor cover again until the instrument is in orbit. The problem with this arrangement is that the cover commands and telemetry interface to the spacecraft electronics cannot be tested during integration using the actual cover. To solve this problem, at least in large part, J12 on the cover logic box is connected to the cover simulator during testing rather than to the actual cover motor. The simulator mimics all functions of the real cover, including the response to all commands and the return of the proper telemetry points to the spacecraft. Thus, the simulator allows the spacecraft functions to be tested.

The simulator does not allow the actual connection of the cover motor cable to J12 on the cover logic box to be verified completely. However, the connection can be tested in part by touching the cover open microswitch. The cover telemetry should respond by changing the cover open telemetry point from 0 to 1. In addition, because the cover is held in place with four screws during integration, it may be possible to send the cover closed command to the instrument. The cover will not move, but the test conductor could hear the cover motor stall and could monitor the current flowing to the motor.

4.2.1.5 Laboratory Test Stand

Figure 15 is a schematic of the testing and calibration stand that is used in the AFGL laboratory to prepare the mass spectrometers. The mass spectrometer sensor, with the cover open, is bolted directly to the vacuum manifold of the test chamber. Several different vacuum pumps are used to evacuate the sensor. Roughing and diffusion pumps are used for the initial pump-down and during testing when the load from the test gases is large. The ion pump is used to maintain the high vacuum during periods when the instrument is not in use.

The QINMS instrument is capable of detecting both positive ions and neutrals. In order to test both functions, two different ion sources are used. One is the internal source that is flown as a part of the flight instrument. The other is an external source mounted inside the test stand vacuum chamber just in front of the sampling grid of the mass spectrometer. The external source uses a simple transverse electron beam, electron impact design that is similar to the internal source.

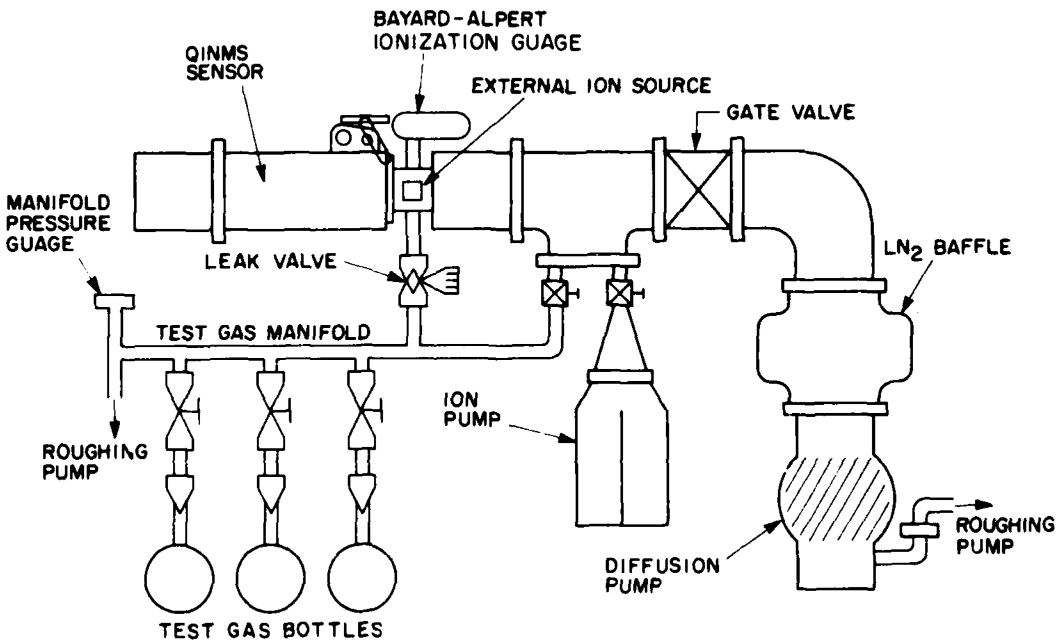

Figure 15. Schematic Diagram of Test Stand

The test gases for both ion sources are mixed in the test gas manifold from lecture bottles or other gas containers. The gases or gas mixtures are introduced into the main vacuum chamber through a variable leak valve. The gate valve is not throttled during these tests. The pressure in both ion sources is taken to be the same as the pressure read by the Bayard-Alpert ionization gauge located near the external source.

4.2.1.6 Portable Vacuum System

Though the QINMS sensor is always transported from the laboratory to the integrating contractor with the cover closed, there is no way to pump the instrument during transportation. There is a good chance that the internal pressure will be too high to turn the instrument on once the instrument arrives at its destination.

Before tests at the integration site can take place, then, the sensor must be pumped out again. This is done with a portable pumping stand that is shipped to the integration site along with the instrument. The portable stand consists of a roughing pump, and may have various combinations of cryo-sorption, turbomolecular, and ion pumps. An appropriate vacuum manifold connects the pumps to the sensor through the small valve that is located on the sensor cover. There is no external ion source or test gas manifold on the portable system.

4.2.1.7 Ion Pump/Controller

Once the sensor has been evacuated to a sufficiently low pressure on the portable vacuum station at the integration site, the pumping is turned over to a very small ion pump that mounts directly on the cover. This small pump has a pumping speed of 2 ℓ/sec, which is sufficient to maintain the high vacuum during integration and testing if the sensor is free of leaks and has been baked thoroughly. It clearly cannot handle any gas load.

The ion pump remains attached to the sensor for most of the integration and tests. It is removed only for specialized tests where the payload must be exactly in its flight configuration, and when the payload is ready for final shipping to the launch site.

A small controller must be attached to the ion pump whenever the pump is in operation. The current drawn by the ion pump, which is displayed on the controller, can be converted to the pressure inside the sensor. Thus, no additional pressure gauges are necessary. The cable between the pump and the controller can be as long as necessary. There is a high voltage hazard where the cable is connected to the ion pump.

4.2.2 GROUND SUPPORT EQUIPMENT CONFIGURATIONS

4.2.2.1 In-House Testing Configuration

Figure 16 shows the sensor, electronics, console, chart recorder, and cover actuator connected to each other in the configuration used for in-house testing or whenever the instrument must operate alone. The sensor is shown attached to the laboratory test stand to emphasize that the pressure inside the sensor must be low enough for safe operation. Because the control console can defeat the barometric switch safety interlock, care must be taken not to operate the instrument at high pressure.

The connection between the sensor and the electronics, from J6 to J10, must always be made whenever the instrument is going to be operated. In the in-house test configuration, J9, the command and power interface, and J7, the telemetry

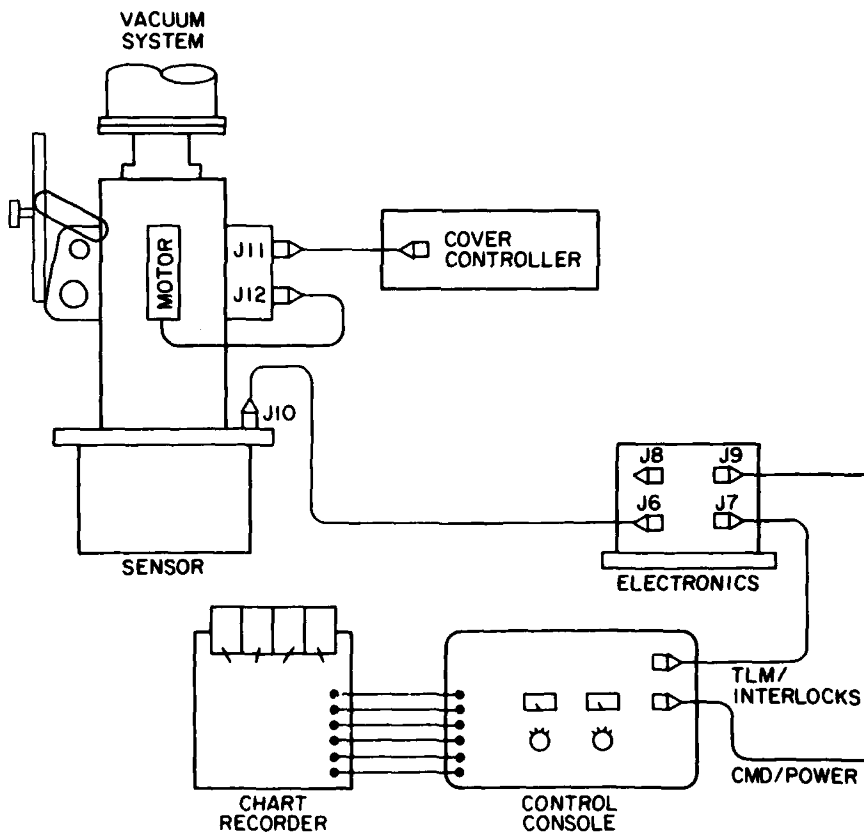

Figure 16. GSE in Laboratory Test Configuration

interface for the console, are both connected to the console. The console thus has complete control of the instrument. J8, the telemetry interface for the spacecraft, is not used.

The chart recorder is shown attached to the output jacks of the console. This is an optional connection in the sense that the instrument can be operated by the console alone. The hard copy of the test results that is produced by the chart recorder will be desirable in most cases, however.

The cover actuator is shown attached to the sensor to emphasize that the actuator is always required to move the cover at all. It must be used, for example, to open the cover before bolting the sensor onto the test stand. It is not required during any tests, however, and perhaps should be detached to avoid accidental attempts to close the cover on top of the test stand vacuum manifold.

4.2.2.2 Integration Testing Configuration

Figure 17 shows the configuration of the ground support equipment that is used for instrument tests during integration of the mass spectrometer into the spacecraft. The drawing assumes that the instrument has already been pumped down by the portable pumping stand, and the little ion pump has been attached to the valve on the cover. The ion pump controller is connected to the pump.

Figure 17 makes no attempt to show the mechanical attachment of the instrument to the spacecraft, but concentrates on the electrical connections. J6 on the electronics box is connected to J10 on the sensor as it was in the in-house testing configuration. J9, however, is now connected to the spacecraft power and command electronics rather than to the control console. J8, which was not used in the in-house testing, is now connected to the spacecraft telemetry electronics. The cables from J6, J8, and J9 are in flight configuration.

J7 is the telemetry interface to the control console. It remains connected to the control console as it was for in-house testing. The cable that carries cover power, commands, and telemetry from the spacecraft electronics to J11 on the cover logic box is in flight configuration. However, J12 on the cover logic box is connected to the cover simulator rather than to the actual cover. The reasons for this were described in Section 4.2.1. Clearly, this last cable is not in its flight configuration.

The most important difference between the in-house testing and the integration testing configurations is that, during integration, the commands, power, and telemetry interfaces are connected to the spacecraft rather than to the console. All control of the instrument is exercised through the spacecraft systems exactly as it will be in flight. The console is attached to the electronics box only to defeat the barometric switch interlocks and to reset several relays inside the electronics after testing. An optional use of the console, for which the chart recorder

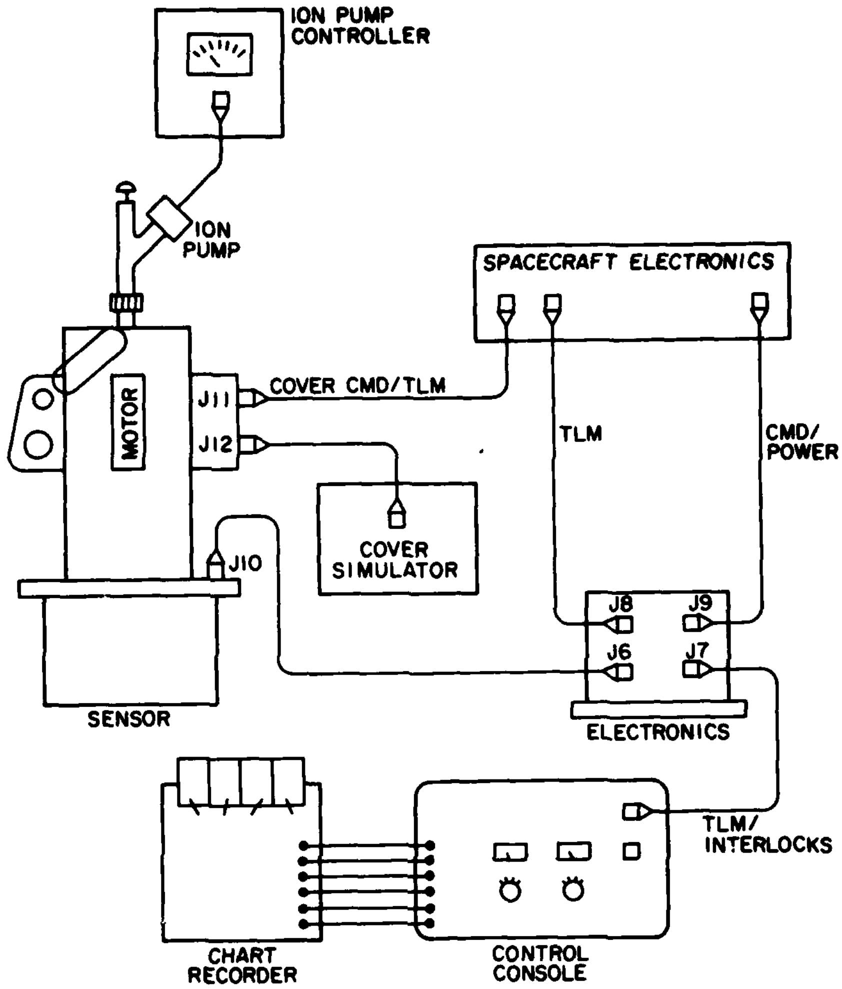

Figure 17. GSE in Integration Test Configuration

may prove useful, is to examine the redundant output of the telemetry that appears there. This could be a very useful function if any problems in the spacecraft telemetry arise. It could also be used to confirm that the spacecraft telemetry gives the same values as the console.

4.2.2.3 Flight Configuration

The flight configuration for the mass spectrometer is shown in Figure 18. Four changes are needed to convert the integration testing arrangement to the flight configuration. First, the cover valve needs to be closed and the ion pump assembly removed. Second, the cable from J7 to the concole must be removed. It is replaced with another connector that serves as a jumper for several internal

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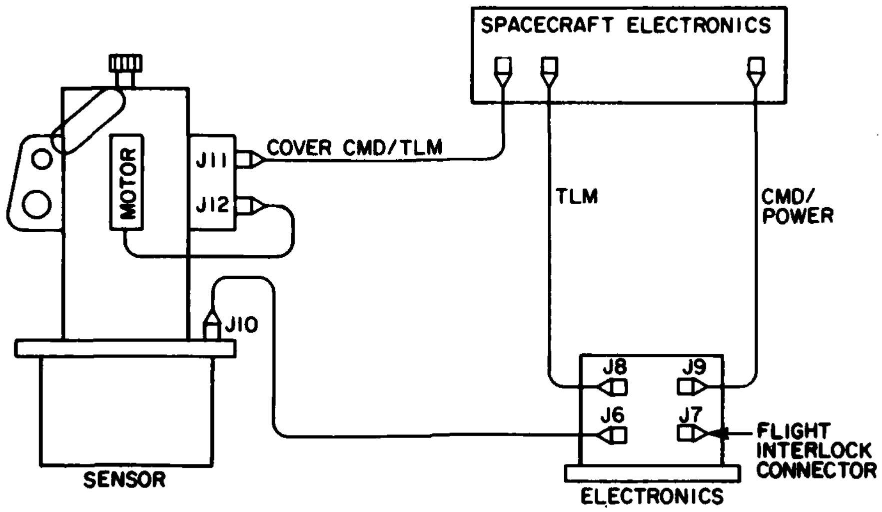

Figure 18. Mass Spectrometer in Flight Configuration

functions. Third, J12 on the cover logic box is attached to the actual cover motor rather than to the cover simulator. Procedures for verifying this connection were described in Section 4.2.1.

These first three operations can occur at the integrating contractor's facility prior to shipment of the spacecraft to the launch site. The fourth and final pre-launch procedure is to remove four screws that hold the cover firmly in place. These will have been installed at AFGL prior to shipping the instrument. To avoid breaking the vacuum in case the cover is accidentally bumped during integration of the spacecraft into the Shuttle Orbiter, the screws should be removed at the last reasonable time before launch.

4.3 Testing Procedures

4.3.1 INITIAL SETUP

After the mass spectrometer has been assembled, it is mounted on the laboratory test stand to be leak checked. Once any leaks in the vacuum chamber have been fixed, the instrument is baked out for the first time to clean the interior. At this stage, the background pressure in the sensor should be in the low 10^{-7} Torr range.

All of the electronic circuits are checked and debugged next. In particular, this involves aligning and balancing the rf circuitry, setting the rf/dc balance, tuning several offset voltages, adjusting the ion source emission current, and adjusting the potentials of the ion source electrodes.

The rf coil and other circuit elements will have been chosen in the construction of any particular instrument to give the desired mass range. Despite this, the actual mass range of the instrument is not known until the initial setup. A series of test gases is introduced into the ion source. The value of the rf voltage at which each of the mass peaks from the test gases appears gives the conversion between rf voltage and mass. The maximum rf voltage can then be converted directly to the maximum mass that the particular mass spectrometer can detect.

The resolution of the mass spectrometer is also determined during the initial setup. As discussed in Section 2.2, the resolution of the mass spectrometer is its ability to tell the difference between adjacent mass peaks. Figure 19 uses three different mass spectra taken on the laboratory test stand to show the effect of resolution of the data. The test gas was a mixture of N_2, Kr, and Xe. The pressure in the ion source was $\sim 8 \times 10^{-6}$ Torr in both cases, and the instrument was operating in neutral mode. The only difference between the two spectra was the rf/dc ratio, which, in turn, controls the resolution of the mass spectrometer.

The difference between the two spectra is most apparent at the high end of the mass range where Xe peaks appear. In the lower resolution spectrum, only four Xe peaks are readily discernible. In the higher resolution spectrum, the mass 128 peak appears as a distinct shoulder to the 129 peak, the 131 and 132 peaks are somewhat separated, and the valley between 134 and 136 goes back to the baseline. Similar differences between the spectra can be seen in the other peaks as well.

Figure 19 also shows how dramatically the sensitivity of the mass spectrometer is affected by resolution. The higher resolution Xe peaks are actually almost a factor of 10 lower in intensity. (Recall that the vertical intensity scale is logarithmic. Ten small divisions equals a factor of 10 in intensity.) This is a graphic demonstration of the tradeoff between resolution and sensitivity. Second, the mass 28 peaks in the two spectra are very similar in both width and intensity. It is typical of quadrupole mass spectrometers that resolution is not necessarily constant across the entire mass range and that changes in resolution generally affect the higher masses more than the lower masses.

The sensitivity of the mass spectrometer can be adjusted directly by varying the voltage across the electron multiplier. As discussed in Section 2.3.4 and shown in Figure 5, this voltage controls the gain of the multiplier. The gain is a very non-linear function of applied voltage: small changes in voltage cause very large changes in gain. Figure 20 shows three spectra, each taken with 5×10^{-5} Torr of an N_2/Kr/Xe mixture in the ion source. The three values of multiplier voltage were 2530, 2750, and 2920 V. The lowest gain, 2530 V, is typical of flight conditions. If necessary, the sensitivity can be increased by an order of

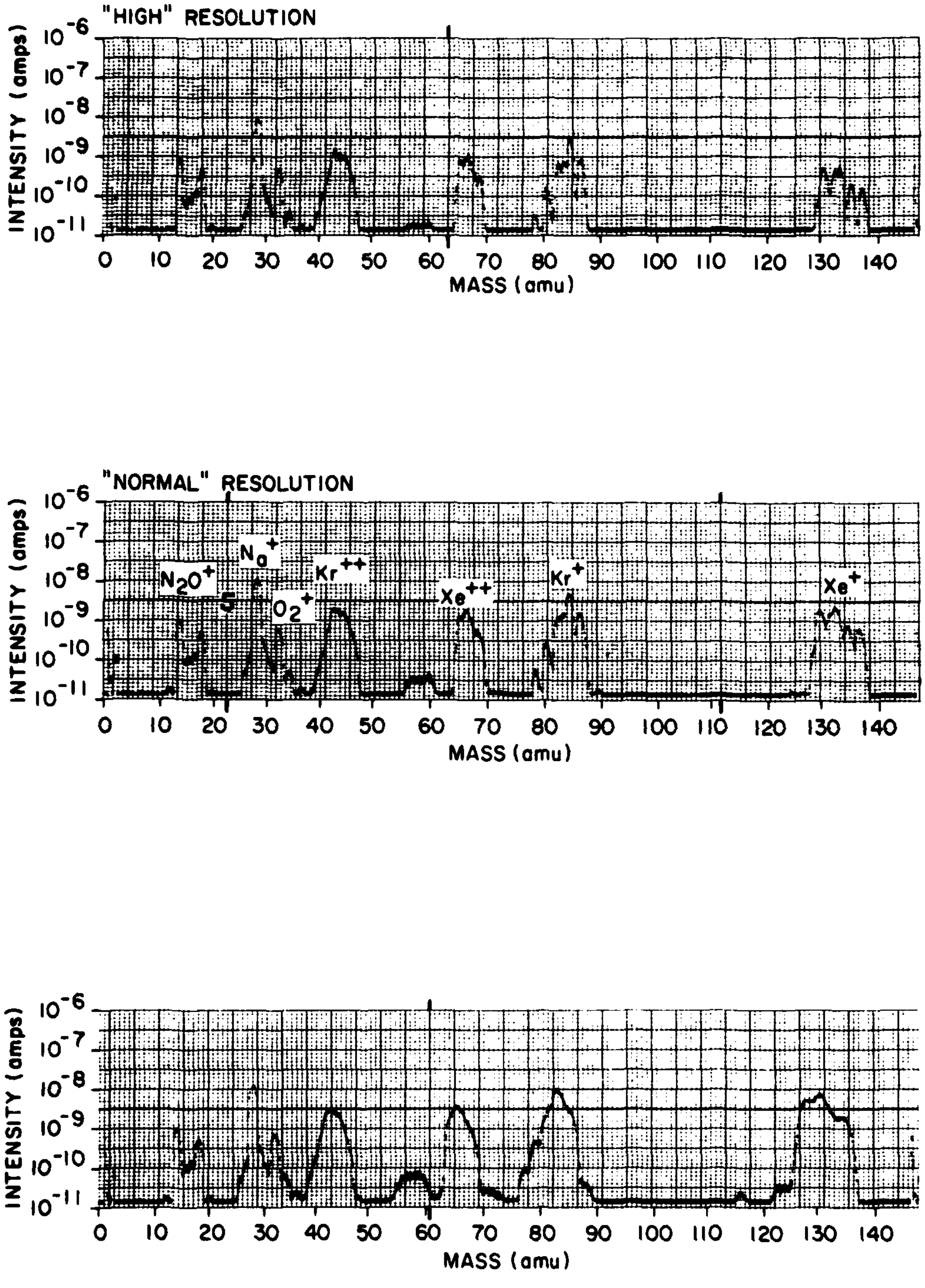

Figure 19. Effect of Resolution on Test Mass Spectra

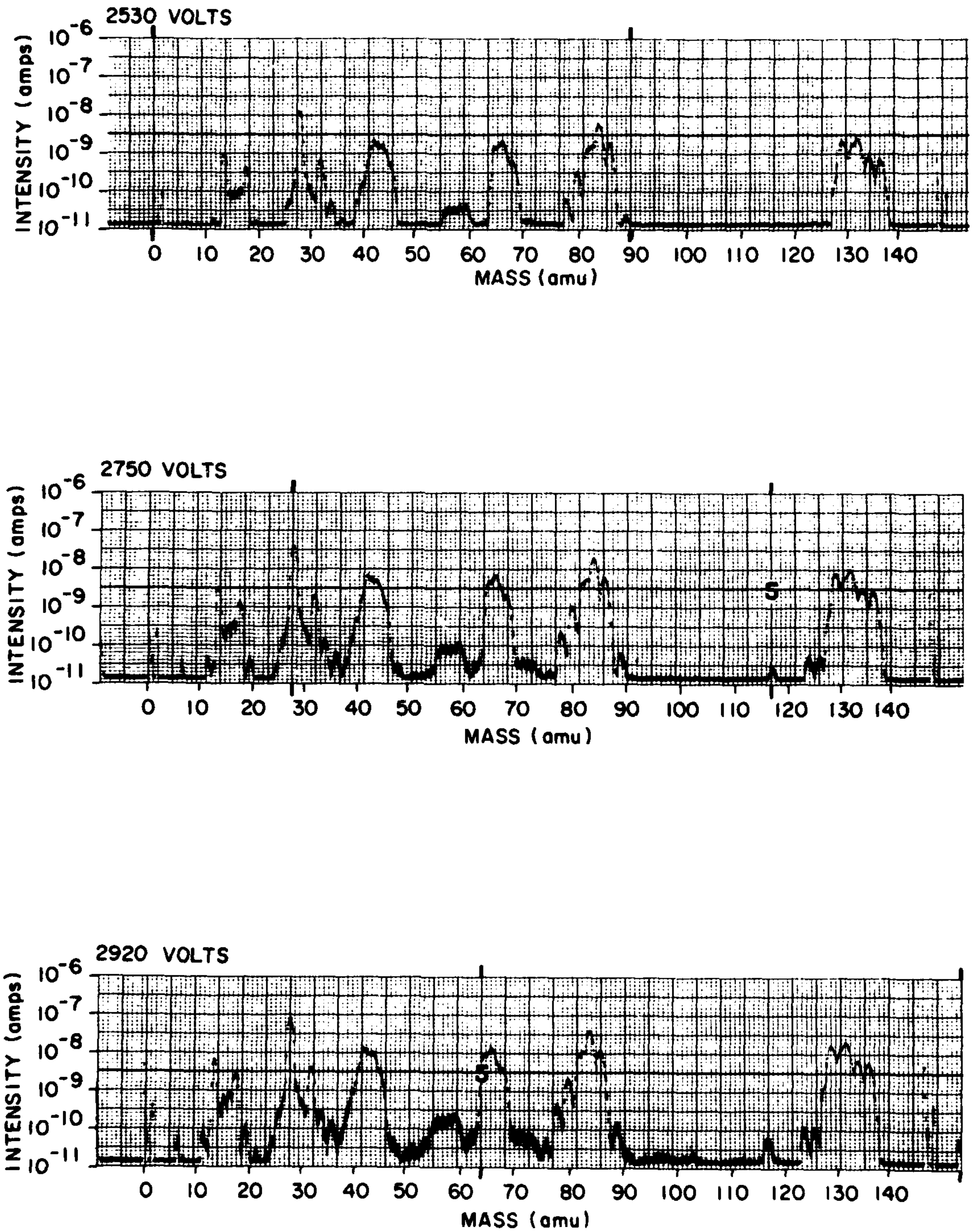

Figure 20. Effect of Multiplier Voltage on Test Mass Spectra

magnitude above this nominal sensitivity. The two tradeoffs of increased multiplier gain are increased noise and background, and possibly shortened multiplier lifetime.

4.3.2 INITIAL CALIBRATION

While the instrument is still mounted on the laboratory test stand, an initial set of calibration experiments is performed. These involve introducing various gases and gas mixtures into the test manifold. The leak valve is then opened by degrees. At many different pressures of the test gas in the ion source region, a mass spectrum is recorded on the chart recorder. In addition, a background spectrum with no test gas in the ion source is recorded. A background spectrum and two calibration spectra are shown in Figure 21. The neutral mode and the ion mode of mass spectrometer operation are both tested. In neutral mode, the interior ion source is activated, whereas in ion mode, the external source is turned on.

Both pure gases and gas mixtures are used. The mixtures are generally half nitrogen and half some other gas. The relative sensitivity of the instrument to the other gas compared to nitrogen is obtained directly from the test spectra. The gases and mixtures usually used for calibration are N_2, He, CH_4, Ar, Kr, Xe, CO_2, O_2, H_2O, Air, N_2/Ar, and N_2/CH_4.

The first step in the reduction of the laboratory calibration data is to convert the height of each peak in the mass spectrum measured in volts to the peak intensity in amps. A logarithmic amplifier calibration curve relating input amps to output volts is shown in Figure 22. A calibrated picoamp current source is used as the input source for the amplifier calibrations.

Each test gas produces a parent ion peak and perhaps a number of fragment ion peaks. The background intensity of each of these peaks is subtracted from the intensity at each pressure. The difference between peak intensity and background is plotted against pressure to give the type of calibration curves shown in Figure 23. The response of the mass spectrometer is typically very linear with pressure until the pressure exceeds 1×10^{-5} Torr. At such high pressures, collisions inside the instrument decrease the signal.

During initial calibrations, no attempt to obtain absolute sensitivities to the various gases is made. Rather, the goal of the tests is to confirm that the response of the instrument to the test gases is linear over the expected range, to show that the relative sensitivity for the various gases is approximately correct, and to determine how much mass discrimination is present. (Mass discrimination is a systematic variation in sensitivity with mass.) If any problems are discovered during initial calibration, they are fixed before continuing with environment testing.

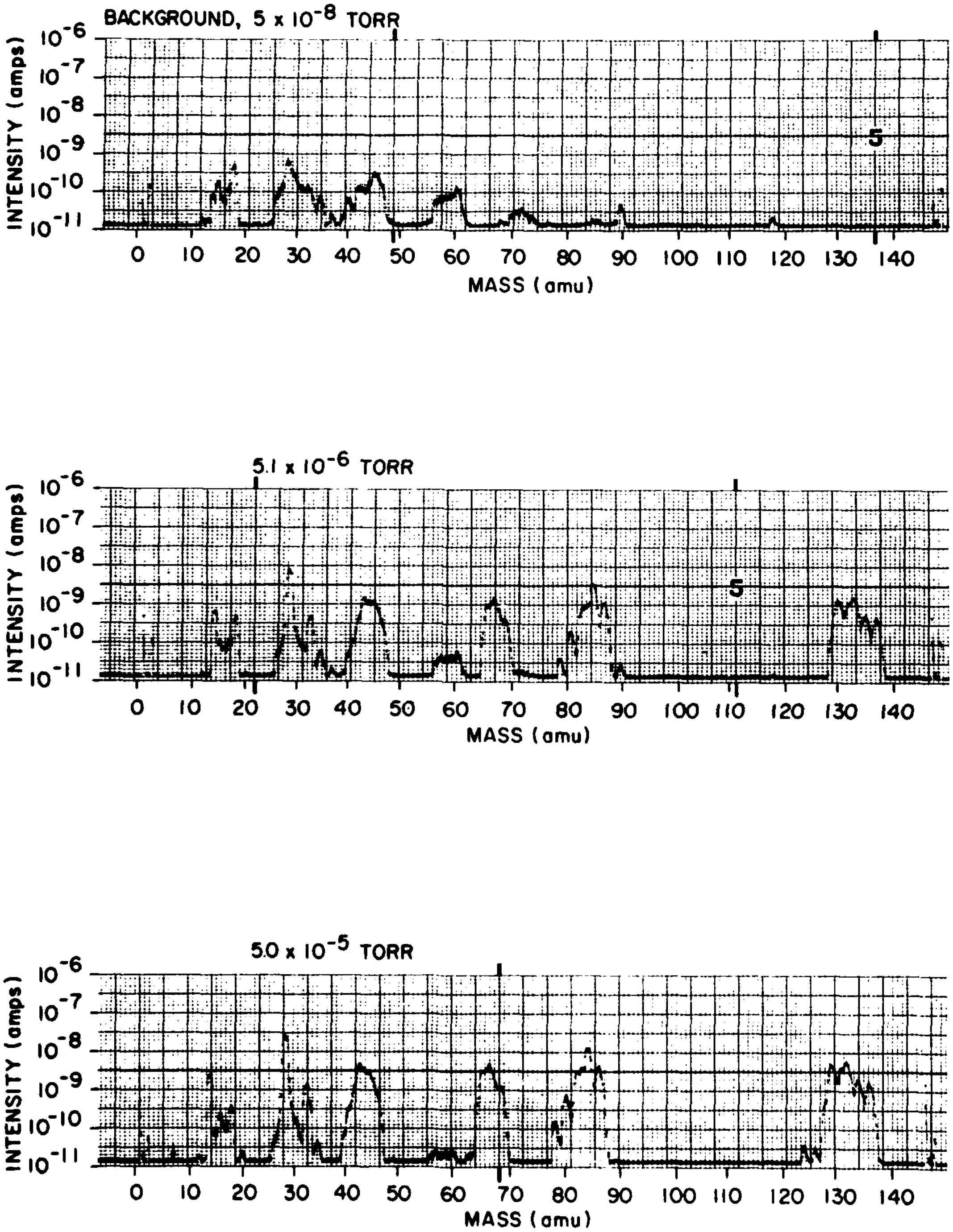

Figure 21. Background and Calibration Spectra

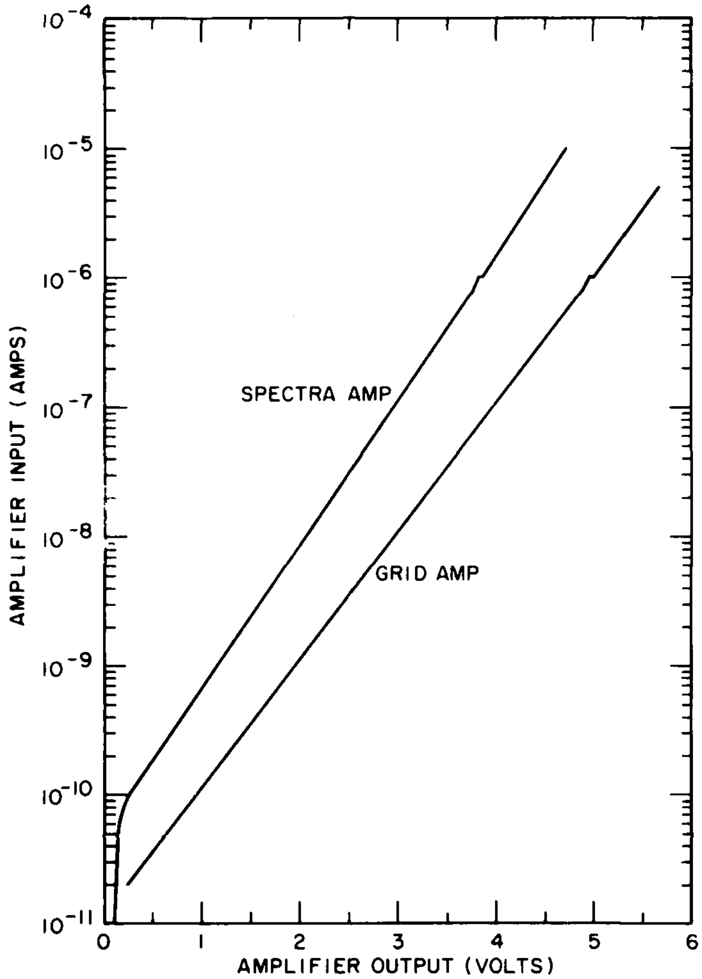

Figure 22. Logarithmic Amplifier Calibration Curves

4.3.3 ENVIRONMENTAL TESTING

A number of additional tests of the instrument are required to confirm that it is able to withstand the rigors of the space environment. These are grouped together into the category of environmental tests. AFGL has facilities for performing the thermal cycling, thermal vacuum, vibration, and shock tests, but the EMI and EMC tests must be done under contract at outside facilities. Typical test conditions are described below. However, each experimental program may have its own individual testing requirements.

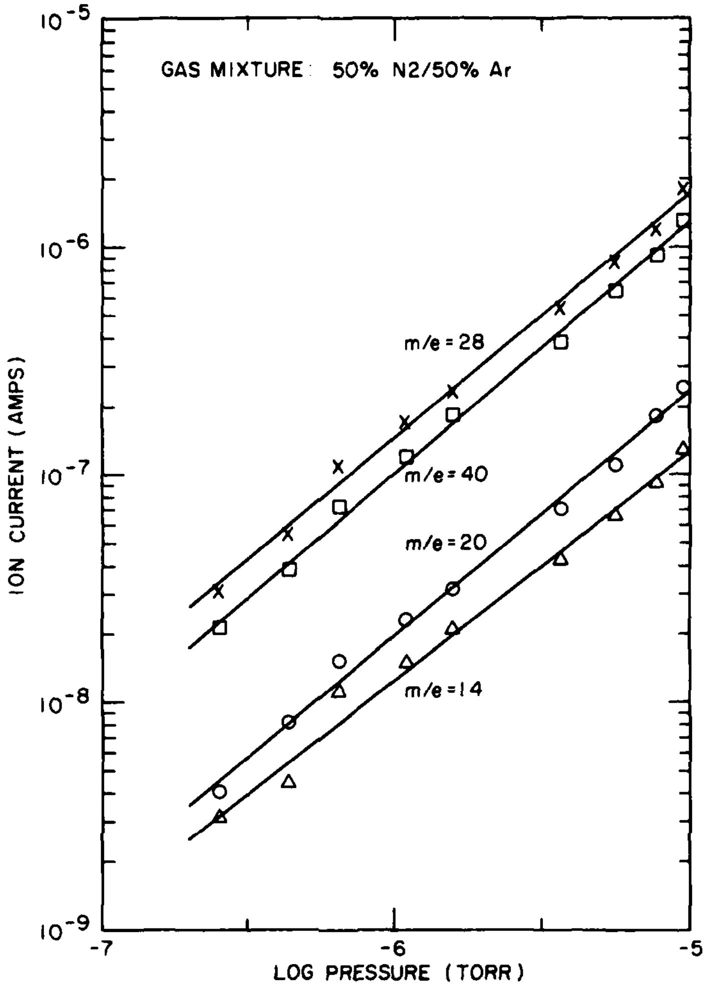

Figure 23. Mass Spectrometer Sensitivity Calibration Curves

4.3.3.1 Thermal Cycling

The temperature of the sensor and the electronics box is cycled repeatedly through the operating temperature range of the instrument to determine whether any components of the electronics are unable to withstand the temperature extremes. The instrument is left mounted to the laboratory test stand and is wrapped with heating tape and cooling coils. The instrument is not operated during the test, but is turned on afterward. In a typical test, the temperature is cycled from 0° to 50°C and then back to 0°C. One such cycle takes about three hours, and includes 30-min periods of holding the temperature at both the upper and lower limits. The whole test consists of six complete cycles.

4.3.3.2 Thermal Vacuum

When the instrument has shown that it can survive the operating temperature extremes, it is tested to show that it operates properly over that range. The instrument is mounted inside a large vacuum chamber fitted with heating lamps and cooling coils. The instrument is turned on and used to collect a sample mass spectrum at several different temperatures. The goal of the test is to make sure that the sensitivity of the instrument doesn't change and that the critical dc and rf voltages that control the mass and resolution do not drift as a function of temperature.

4.3.3.3 Random Vibration and Shock

During launch and perhaps during other handling, the instrument will be subjected to vibrations and shocks. The purpose of the shock and random vibration tests is to insure that the instrument will be able to survive such conditions and to find out whether the instrument has any unwanted vibrational resonances.

The shake table used for these tests is a large piston, the motion of which is controlled electromagnetically by a dedicated computer. The piston can be turned so that its motion is either vertical or horizontal. The motion of the table in any given test is predetermined through the programming of the computer. In a shock test, the piston moves back and forth only once. The speed and amplitude of the motion is determined by the size of the force the instrument must withstand. In the vibration test, the piston moves back and forth randomly for two or three minutes. The "random" motion is actually a superposition of many different sinusoidal frequencies that are sent to the piston simultaneously. The amplitude of motion at each frequency is governed by a preprogrammed power spectrum. A typical power spectrum is shown in Figure 24. An accelerometer is attached to the piece of equipment being tested so that the dynamic response of that piece can be recorded. In this way, any unwanted vibrational resonances can be discovered.

The sensor and electronics box are mounted individually on the shake table. The tests are repeated in each of three different orientations so that all three orthogonal directions are tested. After each part of the test, the instrument is partially turned on to check a few of its functions. Following all of the tests, the instrument may be disassembled partially or completely to find out whether any pieces were broken or dislodged.

4.3.3.4 EMI and EMC

The final environmental test is to show that the instrument does not emit harmful amounts of electromagnetic radiation and that it is not susceptible to radiation emitted by other sources. In the Electromagnetic Interference (EMI)

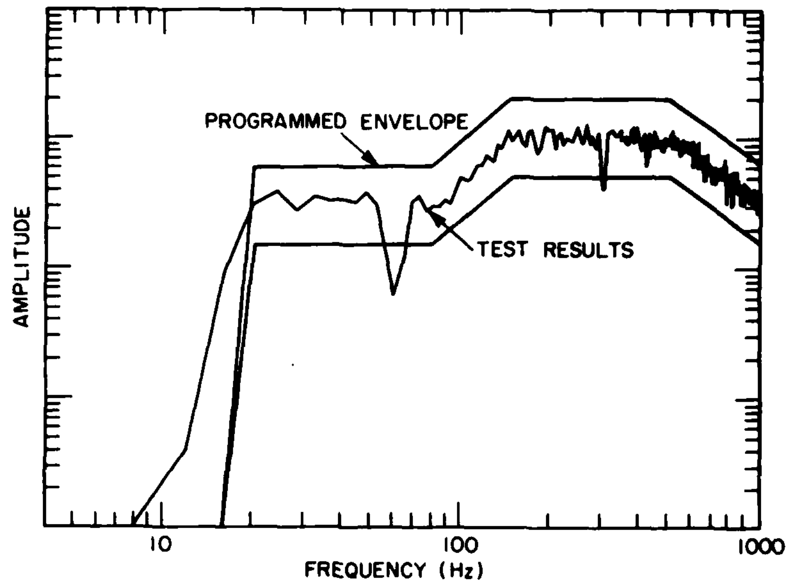

Figure 24. Typical Vibration Test Power Spectrum

test, the amount of radiation throughout a certain frequency range emitted by the instrument is measured. In the Electromagnetic Compatibility (EMC) test, the instrument is operated in a radiation field of certain frequency and intensity to look for any problems. These tests are not done at AFGL.

4.3.4 FINAL CALIBRATIONS

After the instrument has passed all the environmental tests, the calibration procedures on the laboratory test stand are repeated. These final calibrations show whether the instrument characteristics have changed as a result of the other tests, and also provide the calibration factors that will be used for actual data reduction.

The procedures used are the same as those for initial calibration. Calibration factors, which give the amount of current expected for a given pressure of gas in the ion source, are calculated from the linear part of the current vs pressure curves. Pressures are corrected for the mole fraction of the gas in the source (if the gas is a mixture) and for the sensitivity of the ion gauge to the gas. Sensitivities vary by about one order of magnitude from instrument to instrument. The sensitivity to air is generally in the range 10^{-2} to 10^{-1} amp/Torr.

The instrument is left on the laboratory test stand after the final calibrations in order to clean the interior of the vacuum sections. This is done by wrapping the sensor with heating tape and baking it under high vacuum. The instrument is then ready for shipment to the integrating contractor's facility.

4.3.5 INTEGRATION TESTING

This section describes the flow of events that the QINMS experimenters foresee during integration and testing of the mass spectrometer. It is intended as a guide rather than as a description of requirements.

4.3.5.1 Integration Testing Events

Initial Checkout: When the instrument arrives at the integration facility, it is mounted on the pumping station and evacuated. At this point, the electronics can be attached to run a brief bench checkout of the instrument to insure that it works properly.

Integration: The instrument is sealed and removed from the pumping station. The appendage ion pump is attached, but not turned on. If any additional preparation of the instrument is required, such as application of mylar or aluminum thermal control tape, it is done at this point. The flight hardware is then bolted onto the experimental pallet, and all mechanical, electrical, and thermal interfaces are connected.

Full Functional Test #1 (Acceptance Test): A full functional test (see Section 4.3.5.2) is run after integration to test all instrument functions and all interfaces.

Pallet-Level Environmental Testing: The decision to do any pallet-level environmental testing is usually made by program management rather than the QINMS experimenters. Such tests might include thermal vacuum testing, vibroacoustic testing, etc. Environmental testing of the mass spectrometer itself will have been done prior to shipment of the instrument to the integration facility.

It is generally preferable to have the pallet in flight configuration for the environmental tests. Pumping hardware, the ion appendage pump, and any other electrical GSE connections to the instrument will be removed. Because the mass spectrometer will not be under a reliable vacuum for the tests, we do not recommend operating the high voltage functions of the instrument during the tests under any circumstances. The low voltage power supplies may be turned on during thermal vacuum tests, however.

QINMS experimenters do not need to be present during the environmental tests.

Post-Environmental Aliveness Tests: After each of the pallet-level environmental tests, an aliveness test for the mass spectrometer (see Section 4.3.5.3) is generally run.

Full Functional Test #2 (Pre-Shipment Test): The last testing activity at the integration facility before shipment of the pallet to the launch facility is a repeat of the full functional test.

Pre-Shipment Preparation: To prepare the mass spectrometer for shipment to the launch site, the ion appendage pump, any other rough pumping attachments, and the electrical GSE are removed. The shorting flight connector is mated to J7. The four red-tagged cover hold-down screws are not removed.

Launch Site Integration Testing: During factory testing, the interfaces between the mass spectrometer and the experiment support pallet will have been thoroughly tested. The only new interfaces at the launch site are between the shuttle and the pallet. The interfaces between the pallet and the instrument are not affected. If there are ways to verify all connections between the shuttle and the pallet, then there is no need to run full functional tests at the launch site. This has been the case in the past. Only aliveness tests have been run during pallet integration.

If the decision is made to run full functional tests at the launch site, there are several problems that must be solved. First, the instrument must be pumped down. The portable pumping station must be brought close enough to the instrument to make the vacuum connections. A period of at least 24 hours and perhaps as long as several days will be needed for initial pump-down of the instrument. The full functional test could be run at this point with the pumping station attached, or the ion appendage pump could be reattached and turned on. Second, in addition to the pumping equipment, the electrical GSE must also be attached to the instrument to control the interlocks and reset the relays. There may be considerable practical engineering and safety problems involved with attaching all of the GSE to the instrument when it is in the Shuttle payload bay.

Launch Preparation: If any GSE was reattached to the instrument during launch site testing, it must be removed. The shorting flight connector is mated to J7 again, if it was removed during testing. The four red-tagged cover hold-down screws are removed at the latest convenient time before launch.

General Considerations for Integration: For storage periods of less than 2-3 months at the integration facility between integration testing activities, the instrument can stay on the pallet. The ion appendage pump must be attached and operating during this period.

For periods longer than three months, it is desirable to return the instrument to AFGL for storage. We can mount the mass spectrometer on our high vacuum test stand and keep it cleaner than is possible at the factory.

No commands are to be sent to the mass spectrometer under any conditions other than scheduled full functional tests or aliveness tests, even if the power to the instrument is off. The electronics has latching relays that respond to the commands even when the power is off.

4.3.5.2 Full Functional Test

Purpose: Test all instrument functions and interfaces

GSE: Integration testing configuration (see Section 4.2.2.2)

Preparation:

1. Evacuate instrument with pumping station
2. Turn on ion appendage pump
3. Attach test console, chart recorder, cover motor simulator

Time Required: Preparation, 2-3 days; actual test, 1 hour

Comments:

1. Test may be run either with the full pumping station attached or with just the ion appendage pump. The higher pumping speed of the pumping station reduces the chance of damaging the instrument, and is preferable.

2. All commands to the instrument are sent from the spacecraft electronics. Telemetry is received both in the GSE electronics and in the spacecraft telemetry systems. GSE telemetry is monitored real time during the test so that the test can be aborted if necessary. Spacecraft telemetry can be monitored real time and/or after the test.

3. The test procedure is written for two people, the QINMS Experimenter (QE) who controls the GSE and looks at the GSE telemetry and the cover simulator, and the Test Conductor (TC) who looks at the spacecraft telemetry real time and sends commands to the instrument. In actuality, several more people will probably be needed to do all of these jobs.

4. If the test procedure is written into a computer, pauses should be placed in the procedure to make verification of the telemetry easier.

Test Procedure:

1. QE verifies readiness to proceed

2. TC verifies readiness to proceed

3. QE turns on all GSE and enables interlocks

4. TC sends Cover Open command sequence
   a. QE verifies that the cover simulator arm has moved from the closed to the open position.
   b. TC verifies that the cover telemetry shows cover open.

5. TC sends Power On command sequence
   a. QE verifies the following values in GSE telemetry: dc sweep voltage and Vr sweep voltage = pattern; commutator = pattern; rf sweep voltage, high voltage, emission regulator, grid current, and spectra current = 0.
   b. TC verifies the same values in spacecraft telemetry if possible.
6. Pause
7. TC sends Mode 1 (Ion Mode) command
   a. QE verifies dc sweep voltage, rf sweep voltage, Vr voltage, commutator = pattern; high voltage = 2.5; emission regulator, grid current, and spectra current = 0.
   b. TC verifies same points.
8. Pause
9. TC sends Mode 2 (Neutral Mode) command
   a. QE monitors instrument pressure. If pressure gets too high, QE disables interlocks to turn off instrument.
   b. QE verifies dc, rf, Vr, commutator = pattern; high voltage = 2.5; emission regulator = 4.1; grid current = non-zero; spectra current = non-zero pattern.
   c. TC verifies same points.
10. TC sends Mode 1 command 15 sec after the Mode 2 command. QE and TC verify telemetry for Mode 1 as in Step 7.
11. Pause
12. TC sends Cover Closed command sequence
    a. QE verifies that the cover simulator arm moves from the open to the closed position.
    b. TC verifies that cover telemetry shows cover closed.
13. TC sends Power Off command sequence. QE and TC verify that all telemetry = 0.
14. QE disables interlocks, resets relays, and turns off GSE.
15. QE disconnects the cover simulator from the cover logic box and connects the actual flight motor.
16. QE touches the "open" position microswitch. TC verifies that cover telemetry responds.

17. TC sends shortened Cover Close command sequence. (Not to be done every time. This test should be run, at most, once after the final connection of the cover logic box interface cables.) QE listens and watches for motor stall current.

18. Test procedure is repeated as necessary for redundant telemetry or command systems, or for other data formats.

4.3.5.3 Aliveness Test

Purpose: Confirm that the power and telemetry interfaces are intact, at least in part

GSE: Generally not required for aliveness test (see comment 2 below)

Preparation: None

Time: Actual test, 15 min

Comments:

1. No commands other than the power on and power off are to be sent to the instrument during the test.

2. Though the GSE is not required for the test, it may be attached during factory testing so that instrument telemetry can be monitored in two places. The test procedure is written assuming the GSE is available. If not, the spacecraft telemetry will have to be checked real time or post-test.

Test Procedure:

1. QE verifies readiness to proceed

2. TC verifies readiness to proceed

3. QE turns on GSE but does not enable interlocks

4. TC sends Power On command sequence
   a. QE verifies the following telemetry values at the GSE: dc sweep voltage and Vr voltage = pattern; commutator = pattern; rf sweep voltage, high voltage, emission regulator, grid current, and spectra current = 0.
   b. TC verifies the same points in spacecraft telemetry.

5. TC sends Power Off command sequence. QE and TC verify that all telemetry = 0.

6. QE turns off GSE.

4.3.6 POST-FLIGHT CALIBRATIONS

The final test of the instrument occurs after the flight. Calibration curves are run in exactly the same way as for the final pre-flight calibrations. These show whether the instrument changed sensitivity or other characteristics during the flight.

5. FLIGHT OPERATIONS

The scientific goals, experimental procedures, and the operating constraints of each flight of the mass spectrometer will likely be unique. Therefore, it is impossible to give detailed in-flight procedures that apply to every flight. However, there are some general guidelines concerning the operation of the instrument in space that are applicable to all situations.

5.1 Orbital Requirements

There are very few restrictions on the type of orbit that can be used for the mass spectrometer flights. The instrument can operate safely at any orbital inclination and at any alignment to the sun. The major restriction on the orbit is altitude. As was discussed in Section 3.2.2, the instrument should not be operated for long periods at altitudes lower than 180 km, where the pressure in the sensor could be higher than the recommended maximum pressure of 1×10^{-4} Torr.

There is no maximum altitude above which the instrument cannot be safely operated. However, the density of both the ionic and neutral constituents of the atmosphere above 1000 km or so drop below the detection limit of the mass spectrometer.

5.2 Initialization Procedures

One of the last steps in preparing the mass spectrometer for flight, which may occur several months ahead of launch, is to remove the ion pump from the valve on the cover. This leaves the instrument without any pumping. By the time the instrument is in orbit, the pressure inside the sensor could be high enough to cause damage if the instrument were inadvertently turned on. The initialization procedures to be used the first time the instrument is turned on in orbit are designed to make certain the pressure in the sensor is low enough for safe operation.

The initialization procedure consists of the following steps:

1. Open the payload bay doors (or, equivalently, expose the mass spectrometer to the vacuum of free space).

2. A minimum of 30 min after the payload bay doors have been opened, open the QINMS cover. A sequence of three commands to the mass spectrometer is required to open the cover. These commands are:

   a. Select QINMS Cover Open
   b. QINMS Cover Power On
   c. QINMS Cover Power Off

   The first command, Select QINMS Cover Open, must be held for the entire duration of cover motion. The total time needed for the cover to move completely from one limit to the other is ~ 12 sec. We recommend holding the second command, QINMS Cover Power On, for at least 25 sec to insure that the cover has had ample time to open completely.

3. Verify that the cover is open. This can be done using the cover open telemetry monitor. In addition, if the mass spectrometer can be seen from the crew compartment of the Shuttle, the position of the cover can be verified visually. Using both methods is desirable.

4. A minimum of 30 min after the QINMS cover has been opened, turn the instrument on. A sequence of two commands is required to turn the instrument on the first time. These commands are:

   a. QINMS Power On
   b. QINMS Mode 1

   The first command supplies the instrument with +28 V power and activates the low voltage circuits. The second command activates several latching relays inside the instrument that control the high voltage and rf circuits. Once the first Mode 1 command has been sent, the relays remain latched in the activated position. If the instrument must be turned off in flight using the QINMS Power Off command, it can be fully turned on again simply with the QINMS Power On command alone. There is no need to send additional Mode 1 commands after the first to reactivate the high voltage circuits. The instrument will come back on in the same mode that was being used when the power was turned off. Of course, the Mode 1 command will be needed frequently to switch the instrument between ion and neutral measurements.

5.3 On-Orbit Operations

This section gives some guidelines for developing an experimental timeline for the period when the mass spectrometer is in orbit. Of course, it is difficult to give standard operating procedures for the mass spectrometer because of the different requirements of each flight. A detailed timeline will come out of the planning for each flight.

5.3.1 MODE CHANGES

The instrument can be commanded to switch between ion and neutral modes of operation as often as desired throughout the flight, so long as the maximum mode switching rate of one change per minute is not exceeded. It may prove useful for any given flight to design the spacecraft to command a variety of different measurement sequences or patterns of switching between modes. Patterns such as one full orbit of ion data, one full orbit of neutral data, or a full orbit of switching between modes once per minute might be useful.

5.3.2 POWER ON/OFF

The mass spectrometer can be turned off or turned on as often as desired throughout the flight, though switching the power on and off should be subject to the same once per minute restriction as the mode switching. (There is no practical reason why the instrument would be turned on and off so rapidly.) Sending the QINMS Power Off and QINMS Power On commands is all that is required.

5.3.3 CONSTRAINTS

The only additional constraint on the operation of the instrument in the payload bay concerns the pressure. If the payload bay doors need to be closed for any reason during the flight, but will be reopened, the mass spectrometer should be turned off. The cover does not need to be closed. After the payload bay doors reopen, the mass spectrometer should not be turned on again for perhaps 10 or 15 min. This delay will allow sufficient time for the pressure in the sensor to drop below the maximum safe pressure.

There are no further restrictions on the operation of the mass spectrometer in orbit. It can remain on in either mode in all attitudes of the Shuttle, and throughout normal operations such as rocket engine firings, water dumps, fuel cell purges, flash evaporator operations, and so on.

5.4 Preparation for Landing

The sequence of events that prepares the instrument for returning to earth after the mission is nothing more than the reverse of the initialization sequence. Specifically, the following commands should be sent to the instrument.

1. Turn the instrument off. The required sequence of commands is:

   a. Mode 1 command
   b. QINMS Power Off

   The purpose of the Mode 1 command in this case is simply to leave the instrument in a condition where the filament will not burn out if the instrument is accidentally turned on later. The QINMS Power Off command removes all power from the instrument.

2. Close the QINMS Cover. Three commands are required:

   a. Select QINMS Cover Closed
   b. Cover Power On
   c. Cover Power Off

   Again, the first command, Select QINMS Cover Closed, must be held for the duration of the cover motion. The cover power should remain on for 25 sec.

3. Verify that the cover has closed both visually, if possible, and by looking at the cover telemetry.

5.5 Post-Landing Operations

Nothing special needs to be done to the QINMS instrument after landing. It can simply remain attached to the Shuttle or to the experiment pallet for as long as necessary after the flight. When it is time to remove the instrument from the pallet, it can simply be unbolted and handed to the QINMS experimenters. The four cover hold-down screws will probably be replaced for transportation of the instrument back to AFGL. When the instrument has been returned to AFGL, its condition will be checked and it will be mounted on the laboratory test stand for post-flight calibration experiments.

6. DATA REQUIREMENTS

This final chapter of the report discusses the data requirements for the flight of a QINMS instrument on the Space Shuttle. Since the data collection and analysis for the in-house testing is handled by AFGL personnel in the laboratory, the chapter will be concerned with data from the integration tests and the flight.

6.1 Integration Testing Data

AFGL experimenters need access to all of the QINMS telemetry generated during an integration test. However, the data need not be available real time during the test. The data rate is large enough that an experimenter could not evaluate the data real time, anyway. The data will generally be collected by a computer dedicated to the integration testing. This computer should be programmed to provide a print-out of the QINMS data. A convenient format for the print-out is to have the QINMS telemetry points labeled across the top of each page. The volume of data in this print-out will necessarily be quite large, especially if the aperture amp is being sampled at 1000 Hz. However, the total duration of the integration tests need only be 10-15 sec each in ion mode and neutral mode.

The only possible reason to provide real-time data display for use during integration tests is protection of the instrument. If any of the data points are out of limits, then the test could be aborted by the experimenter. However, as discussed in Section 4.2.2, the control console and chart recorder can be attached to the mass spectrometer during the integration testing. The GSE may provide all the real time data required.

6.2 Flight Data

A great deal of information about the flight is required to reduce and analyze the QINMS flight data. This data can be categorized as scientific data, Shuttle operations data, and other data. The requirements are summarized in Table 9.

6.2.1 SCIENTIFIC DATA

It is obvious that we will need the full telemetry from the QINMS instrument. As discussed in Section 3.5, the total telemetry rate may depend on the specific design of the telemetry system, but should not exceed about 12 kbps.

If other scientific instruments are carried aboard the spacecraft, access to the data from those experiments may prove very useful in the analysis of the QINMS data.

6.2.2 SHUTTLE OPERATIONS DATA

We need to know the position of the Shuttle in orbit at each point that QINMS data is taken, and also the roll, pitch, and yaw angles of the Shuttle with respect to the velocity vector. These ephemeris and attitude data are usually supplied in the Orbiter Auxiliary Data.

Since orbiter operations affect the measurements made by the mass spectrometer, we need to know the times of all orbiter contamination events such as engine firings, water dumps, flash evaporator operations, and fuel cell purges.

Table 9. Flight Data Requirements

Data Product	Accuracy	MET Timing Accuracy (sec)
QINMS Data	8-bit A/D	0.01
Other Science		
Shuttle Ephemeris		
Latitude	1 deg	1
Longitude	1 deg	1
Altitude	1 km	1
Shuttle Attitude		
Roll, Pitch, Yaw	1 deg	1
Shuttle Contamination		
OMS, RCS Firings		0.01
Water Dumps		1
Flash Evaporator		1
Fuel Cell Purges		1
Etc.		1

6.2.3 OTHER DATA

Finally, geophysical events also affect the measurements made by the mass spectrometer. It may prove useful in the data analysis to have available tables of geophysical data such as solar activity from the period of the flight. Data from ground based observation sites such as radar facilities may prove valuable as well.

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